CHAROPHYTE BIOSTRATIGRAPHY OF THE PURBECK AND WEALDEN OF SOUTHERN ENGLAND

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ABSTRACT. The distribution of charophyte assemblages in the Purbeck and Wealden sequence of southern England has been established from borehole samples from the Weald and from outcrop material collected in Dorset, Wiltshire and on the Isle of Wight. Of the twenty-one taxa represented, three are new: *Globator rectispirale*, *Clypeator britannicus* and *Sphaerochara andersonii*; three new combinations are proposed: *Globator praecursor*, *Globator protoincrassatus* and *Atopochara triquetra*. The Chinese Valanginian species *Flabellochara xiangyunensis* is recognized for the first time in Europe. In the context of the phylogeny of the Family Clavatoraceae, *G. rectispirale* represents the Jurassic ancestor of the *Globator* lineage and a separate origin is suggested for both *Flabellochara* and *Clypeator*. The correlations established with the Tethyan realm locate the Jurassic–Cretaceous boundary within the Lulworth Formation of the Purbeck Limestone Group; in this context, the whole 'Purbeck' sequence of Swindon (Wiltshire) is attributed to the Upper Tithonian. The distribution of Clavatoraceae indirectly confirms the contemporaneity of the Boreal *Galbanites kerberus* and *Titanites anguiformis* with the Tethyan '*Durangites*' ammonite zones. For the Wealden Supergroup, the charophyte data affirm the Hauterivian–Barremian boundary at the base of the upper division of the Weald Clay and the Upper Barremian is identified at the base of the Vectis Formation of the Isle of Wight.

THE charophytes of the Purbeck and Wealden successions of southern England have received little attention since they were first recognized by Forbes (1851) in the Purbeck Beds of Mupe Bay (Dorset). A preliminary report on the Purbeck Beds Characeae was published by Reid and Groves (1916), who established the genus *Clavator*, subsequently discussed by Groves (1924). The only detailed study of Purbeck charophytes to date has been by Harris (1939) who reviewed previous work and provided descriptions of assemblages from the Dorset coast and inland sections, as well as from the Vale of Wardour and quarries at Swindon (Wiltshire). More recently, Barker *et al.* (1975) discussed the depositional environment of the Charophyte Chert at the base of the Great Dirt Bed, 4 m above the base of the Purbeck Beds at Portesham Quarry (Dorset) and described the supposed new species *Clavator westii* from indeterminate Clavatoracean material. Harris (1939), on the basis of studying 'Middle' and 'Upper' Purbeck charophyte associations, stated that they did not exhibit major evolutionary changes and concluded that 'these beautiful little fossils [gyrogonites] are likely, in general, to have only slight stratigraphic value'. In contrast to this view, further research on charophyte gyrogonites, following the pioneer work of Peck (1957) and Grambast (1972, 1974), has revealed their stratigraphical importance for dating and correlating Cretaceous and Palaeogene non-marine deposits.

Preliminary studies of charophytes recovered from cored boreholes in the Weald showed that part of the Purbeck sequence could be attributed to the Berriasian Stage and that the upper part of the Weald Clay of the Wealden Supergroup belonged to the Barremian Stage (Feist *in* Lake *et al.* 1987). In this paper we present the results of our research to date on the charophyte biostratigraphy of the Purbeck and Wealden outcrop and subcrop successions of southern England. These results have been directly integrated with the ostracod zonal and faunicycle scheme of Anderson (1985), as charophytes and ostracods are commonly found associated in the same sample. We also review evolutionary trends among the charophyte family Clavatoraceae.

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MATERIALS

The greater part of the charophyte specimens was separated from the residues of microsamples taken from cored boreholes in the Weald; most were taken from the ostracod collection of the late Dr F. W. Anderson at the British Geological Survey. For the Dorset, Isle of Wight and Swindon localities, new material collected by M. Feist from exposure has been studied, in addition to specimens from the Natural History Museum (London) and Senckenberg Museum (Frankfurt am Main, Germany). The borehole material from the Weald, the types of the new taxa described herein and the specimens figured in Plate 1, figures 1–2 and 4–8 are housed at the British Geological Survey, Keyworth, UK; the specimens figured in Plate 1, figures 16–17 at the Natural History Museum, London, UK; and the specimen figured in Plate 1, figure 9 at the Senckenberg Museum, Frankfurt am Main, Germany. The other samples are deposited at the Laboratoire de Paléobotanique, Université de Montpellier II, France, under the symbol CF.

EVOLUTIONARY TRENDS AMONG THE CLAVATORACEAE

The Clavatoraceae is a Mesozoic charophyte family characterized by the gyrogonite having a supplementary calcified cover of vegetative elements, known as the utricle. As shown by Grambast (1974) in his analysis of three phylogenetic lineages through the Cretaceous, it is the utricle that underwent evolutionary change. These lineages represent such remarkable examples of progressive evolution that they have been interpreted by Martin-Closas and Serra-Kiel (1991) as 'evolutionary species' (*sensu* Wiley 1978). However, this concept has no formal taxonomic status and is not appropriate to biostratigraphical studies.

The Clavatoraceae are subdivided into three subfamilies, according to the wall structure and the symmetry of the utricle. In the Echinocharoideae and Atopocharoideae, the utricle wall is composed of only one layer of three symmetrically arranged cells. In the former subfamily, the utricle comprises unjoined cells, whereas in the latter the cells are coalescent and entirely cover the gyrogonite inside. Our material comprises three representatives of the Atopocharoideae: the genera *Globator*, *Perimneste* and *Atopochara*. The Clavatoroideae differ from the two former subfamilies by the complexity of the utricle wall, which comprises two layers, with internal canals in the most evolved species, and by a bilateral symmetry. A three-fold symmetry can become superimposed secondarily, as in *Triclypella*. Most Clavatoraceae from southern England belong to this subfamily, namely *Nodosoclavator*, *Clavator*, *Flabellochara*, *Clypeator*, *Triclypella* and *Ascidiella*.

The new data from the Purbeck charophyte floras of southern England complement existing data on the *Globator* lineage, and allow us to propose a separate origin for the two genera of the *Flabellochara–Clypeator* lineage (Grambast 1970, 1974). Our new data for *P. horrida* and *A. triquetra* do not modify the evolutionary succession outlined by Grambast (1967) for the *Perimneste–Atopochara* lineage, and so will not be discussed in this section.

Globator *lineage*

This series shows the evolution from the Tithonian *Globator rectispirale* to the Barremian *G. trochiliscoides* by reduction in the number of utricle cells and by progressive acquisition of spiralling (Pl. 1, figs 1–8). Only the oldest forms have so far been found in southern England.

G. rectispirale sp. nov. is the oldest and most primitive representative of the *Globator* lineage; each utricle comprises twenty-four vertical cells, without any indication of spiralling, when viewed both laterally and apically (Pl. 1, figs 1, 5). It is found in the Fairlight Borehole at 317·6–317·9 m. As reported below, the occurrences of this form outside the British Isles, have all been attributed to the Upper Tithonian.

G. praecursor (Mojon) comb. nov. occurs at 296·0–296·3 m in the Fairlight Borehole, and equivalent beds in the Warlingham, Broadoak and Brightling boreholes. It has the same utricle structure with twenty-four cells, but the upper elongated cells have begun to spiral (Pl. 1, figs 2, 6).

This form has been dated as Lower Berriasian in the Goldberg Formation in the Jura Mountains, where it is the index species of Mojon's Zone M1. Accordingly, the Jurassic–Cretaceous boundary can be recognized in southern England between the beds with *G. rectispirale* and with *G. praecursor*, near to the base of the Purbeck sequence.

G. protoincrassatus (Mojon) nov. comb. occurs at 293·2–293·5 m in the Fairlight Borehole, as well as in Bed 70 of Clements (*in* Cope *et al.* 1969) of the higher part of the Soft Cockle Member of the Lulworth Formation of Dorset. The utricle is still composed of twenty-four cells, but the three basal cells are shorter and the upper ones have become even more strongly spiralled (Pl. 1, figs 4, 8). This taxon is the index-species of Mojon's Zone M2, considered to be Lower Berriasian.

The subsequent stages of the *Globator* lineage, which have been reported from Spain (Grambast 1966, 1974; Martin-Closas and Grambast-Fessard 1986) and North America (Peck 1957) are missing in the Purbeck–Wealden succession of the British Isles; this absence may be explained by a local excess in salinity and lack of calcium carbonate in Hastings Beds and Weald Clay times.

Flabellochara *and* Clypeator *lineages*

The subdivision of the *Flabellochara–Clypeator* lineage proposed here differs from Grambast's phylogeny, in that *Clypeator* is not considered to be a descendant of *Flabellochara* because at various localities it has been found that *Flabellochara* appeared later than *Clypeator*. However, the main phylogenetic tendencies are the same as those demonstrated by Grambast (1970).

In the oldest of the Clavatoraceae, *Nodosoclavator* sp., only the internal layer of the utricle is developed, and is composed of nodules covering the spiral cells of the gyrogonite. *Nodosoclavator* appeared in the Oxfordian (Feist and Schudack 1991) and persisted until the Barremian.

In the Upper Tithonian, *Clypeator* (*C. discordis*) appeared. In this genus, the central basal cell of each side of the utricle is subdivided and the lateral pore occupies a central position (Pl. 2, figs 5–6). The evolutionary trend continued by lengthening and spiralling of the upper basal cells, from the late Tithonian, when *C. discordis* appeared, to the Albian *C. caperatus* and *C. lusitanicus*. *Triclypella* (Pl. 2, figs 1–3) represents a side branch of *Clypeator* (Grambast 1970). In the present state of knowledge of the few documented Upper Jurassic charophyte floras, the only possible transitional form between *Nodosoclavator* and *Clypeator* would be *Echinochara peckii*. However, the latter differs fundamentally from *Clypeator* in its utricle structure, built on a six-rayed mode of symmetry (Peck 1957; Grambast 1974), instead of the bilateral symmetry of *Clypeator*, and devoid of a nodular internal layer. The *Clypeator* and *Clavator–Flabellochara* lineages seem to have derived from an as yet undiscovered common Late Jurassic ancestor.

The *Clavator–Flabellochara* lineage starts with *Clavator* aff. *reidii*, found in the Upper Tithonian; 'aff.' indicates that the utricle is not yet completely constituted (Pl. 1, figs 9–10); the vegetative cells do not reach the apex of the 'nodosoclavatoroid gyrogonite' (*sensu* Schudack 1990, for *Nodosoclavator*).

In the Lower Berriasian *Clavator reidii*, the two-layered utricle is attained; it consists of vertical cells originating from a basal very short cell and joining themselves at the apex (Pl. 1, figs 11–13). Within populations of *C. reidii*, incompletely constituted utricles morphologically similar to *C.* aff. *reidii* are commonly found. However, these morphotypes do not represent the Tithonian species, because, in the latter, the utricle never reaches the apex of the gyrogonite, whereas, in the Berriasian, populations of *Clavator* generally include typical specimens with complete utricles. Such populations are found notably in the Hils Serpulit of north-western Germany (Feist and Schudack 1991). The immature morphotypes can be regarded as reminiscent of the ancestral Tithonian stage. *Flabellochara* was derived from *Clavator* by addition of two cells on each adaxial side of the utricle and by the development of radiating, instead of vertical, upper cells. In *Flabellochara* (Pl. 1, figs 14–21), the small cells surrounding the lateral pores always remain small, unlike in *Clypeator*.

SYSTEMATIC PALAEONTOLOGY

The three families in existence during Late Jurassic to Early Cretaceous times are all represented. As commonly found for this time, Clavatoraceae are dominant, both in number of species and abundance, the Porocharaceae and Characeae remaining small and unornamented forms. Overall, twenty-one species have been identified in our material.

Family POROCHARACEAE Grambast, 1962
Subfamily POROCHAROIDEAE Grambast, 1961

Genus POROCHARA Mädler, 1955

Porochara maxima (Donze) Donze, 1958

Plate 2, figure 21

1955 *Aclistochara maxima* Donze, p. 289, pl. 13, figs 6–7.
1958 *Porochara maxima* Donze, p. 180.

Distribution and range in southern England. Weald: Warlingham Borehole (612·1 m), upper part of the Broadoak Calcareous Member, Lulworth Formation. This level was referred to the Netherfield ostracod faunicyle (Anderson *in* Worssam and Ivimey-Cook 1971; Anderson 1985). The Berriasian age of this horizon is deduced from records of the species from other areas.

Other occurrences. Berriasian of the Jura (Donze 1955; Mojon 1989), Spain (Brenner 1976; Schudack 1987*a*) and Sardinia ('*Musacchiella maxima*') of Colin *et al.* (1985).

EXPLANATION OF PLATE 1

Figs 1, 5. *Globator rectispirale* sp. nov. Fairlight Borehole, Sussex, 317·6–317·9 m; Broadoak Calcareous Member. 1, MPK 8888, paratype; apical view. 5, MPK 8919, holotype; lateral view.

Figs 2, 6–7. *G. praecursor* (Mojon) comb. nov. Fairlight Borehole, Sussex; Broadoak Calcerous Member. 2, MPK 8889; depth 296·0–296·3 m; apical view. 6, MPK 8920; depth 296·0–296·3 m; lateral view. 7, MPK 8891; depth 293·2–293·5 m; lateral view.

Figs 3–4, 8. *G. protoincrassatus* (Mojon) comb. nov. 3, CF 2911-1; Swanage, Dorset; upper Soft Cockle Member; lateral view. 4, 8, Fairlight Borehole, Sussex, 293·2–293·5 m; Broadoak Calcareous Member. 4, MPK 8890; apical view. 8, MPK 8921; lateral view.

Figs 9–10. *Clavator* aff. *reidi* Groves. Exposure III, Town Gardens Quarry, Swindon, Wiltshire; Chara Marls; lateral views; 9, SMF 44798. 10, CF 2791b-1.

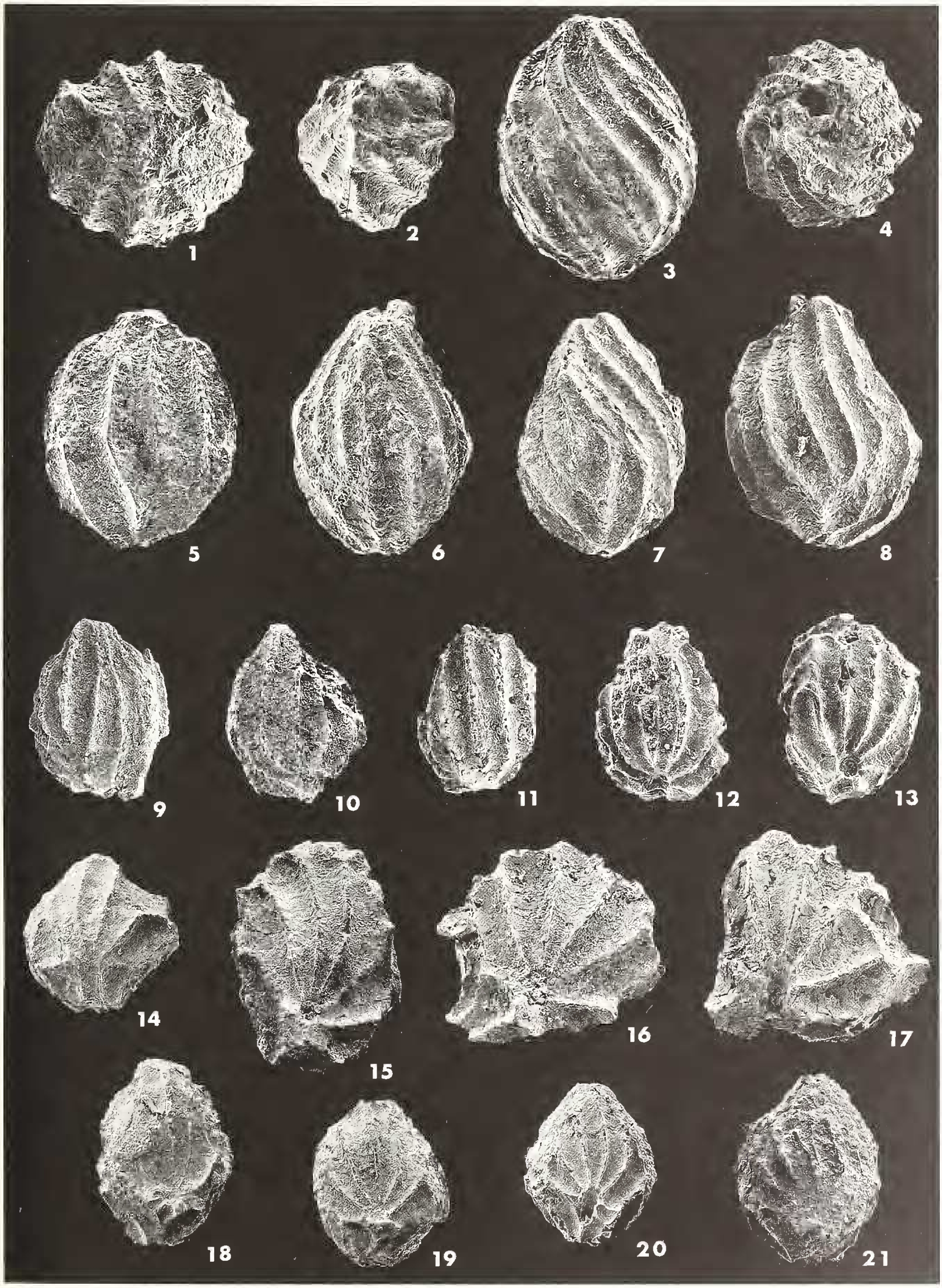
Figs 11–13. *Clavator reidi* Groves. Fairlight Borehole, Sussex, 280·1–280·4 m; Broadoak Calcareous Member; lateral views. 11, MPK 8892. 12, MPK 8895. 13, MPK 8896.

Figs 14–15. *Flabellochara grovesi* (Harris). Lulworth Formation, Plant and Bone Beds Member; lateral views. 14, MPK 8893; Fairlight Borehole, Sussex, 273·4 m. 15, MPK 8894; Broadoak Borehole, Sussex, 71·50–72·00 m.

Figs 16–17. *Flabellochara grovesi* (Harris). NHM V 26181-3 and NHM V 26181-4; Poxwell Road cutting, Dorset; Bed 33; lateral views.

Figs 18–21. *Flabellochara xiangyunensis* Wang *et al.* Wadhurst Clay; lateral views. 18–19, Wadhurst Park No. 3 Borehole. 18, MPK 8897; 7·3–7·6 m. 19, MPK 8898; 6·7–7·0 m. 20, MPK 8899; Glynleigh Borehole, 59·00–59·50 m. 21, MPK 8900; stream section near Warninglid.

All ×45, except figs 14, 19 and 20, ×48, and fig. 18, ×43.



FEIST *et al.*, charophytes

Family CLAVATORACEAE Pia, 1927
Subfamily ATOPOCHAROIDEAE Peck, 1938, emend. Grambast, 1969

Genus GLOBATOR Grambast, 1966

Globator rectispirale Feist, sp. nov.

Plate 1, figures 1–5

1971 *Globator maillardi* (Saporta); Ramalho, pl. 32, fig. 7.
1981 *Globator maillardi* Saporta; Benest, p. 1288.
1985 *Globator* cf. *maillardi* De Saporta; Benest, p. 363.
1989 *Globator maillardi praecursor* Mojon, *pars*; Mojon *in* Détraz and Mojon, p. 54, lines 8–9.

Holotype. MPK 8919, British Geological Survey, Keyworth (Pl. 1, fig. 5).

Paratype. MPK 8888 (Pl. 1, fig. 1).

Type horizon and locality. Lulworth Formation, Broadoak Calcareous Member, Fairlight Borehole, Sussex, 317·6–317·9 m.

Derivation of name. From the shape of the upper cells of the utricle, which are quite straight in the new species, but always spiral to some extent in other *Globator* representatives.

Diagnosis. Utricle of *Globator* composed of three units, each comprised of one central basal cell, bearing three upper cells, flanked by two lateral basal cells each bearing an upper cell. Length of the central basal cells equal to 50–52 per cent. of the utricle length. Upper cells straight, and do not reach the apex. General shape globular to ovoid. Dimensions: 775–1025 μm long, 675–825 μm wide; L/W ratio varying from 1·1 to 1·4.

Remarks. This Tithonian species of *Globator* differs from other representatives of the genus by its utricle with very large basal cells and completely straight upper cells. It represents the most primitive grade of the *Globator* lineage.

Distribution and range in southern England. Weald: Fairlight Borehole (317·6–317·9 m), Broadoak Calcareous Member, Lulworth Formation, below the correlative of the Mountfield Adit Limestone. Mojon's identified ostracods in the associated residue (*Cypridea dunkeri papulata* (aberrant), *Damonella pygmaea*, *Fabanella boloniensis*, *Mantelliana purbeckensis* and *Rhinocypris jurassica*) indicate Ostracod Assemblage 1 of Anderson (1985). Only known record to date.

Other occurrences. Algeria: Chellala Mountains, Mahjouba Formation (Tithonian), from 50–60 m below beds with an A2/A3 calpionellid subzonal assemblage (Benest 1981, 1985).

Southwest Portugal: Brouco section, Sintra area, 'Infravalanginian' beds with *Anchispirocyclina* (Ramalho 1971). These beds were referred to the Lower Cretaceous on ostracod evidence; however, *Mantelliana purbeckensis*, the species on which this correlation is based (Rey *et al.* 1968), appeared in the Weald in the ostracod assemblage of the Gypsiferous Beds (Anderson 1985). The former beds are now considered to be Upper Jurassic (Rey, pers. comm. 1991), which agrees with the presence of Upper Tithonian calpionellids in the lower *Anchispirocyclina* beds in the Algarve (Rey 1982, 1983).

Globator praecursor (Mojon) comb. nov.

Plate 1, figures 2, 6–7

1987 *Globator maillardi* (Saporta); Feist *in* Lake *et al.*, p. 14.

1989 *Globator maillardi praecursor*; Mojon *in* Détraz and Mojon, p. 53, figs 5M–5R, *non* p. 54, lines 8–9.
1991 *Globator maillardi praecursor*; Feist and Schudack, p. 502.

Holotype. Détraz and Mojon (1989, fig. 5M).

Emended diagnosis. Utricle of *Globator* composed of three units each comprised of one central basal cell, bearing three upper cells, flanked by two lateral basal cells each bearing an upper cell. Length of central basal cells equal to 33–34 per cent. of the utricle length. Upper cells oblique, slightly curved and reaching the apex. General shape ovoid. Dimensions: 850–1000 μm long, 600–700 μm wide. L/W ratio varying from 1·4 to 1·8.

Remarks. This form is remarkably stable in its different morphological characters in localities as distant as Jura, north-west Germany and southern England. A combination of this wide geographical distribution and a very short stratigraphical range makes *G. praecursor* a charophyte index for the basal Berriasian. These factors combine to justify raising this form to specific rank.

Distribution and range in southern England. Weald: Warlingham Borehole (625·1 m), Fairlight Borehole (296·0–296·3 m), Broadoak Borehole (111·50–112·00 m) and Brightling No. 27 Borehole (270·6 m). All occurrences were in the Broadoak Calcareous Member, Lulworth Formation; in the Broadoak Borehole they were from immediately above the Mountfield Adit Limestone. Mojon's identifications of the ostracods in the Fairlight Borehole sample include *Cypridea dunkeri inversa* and *Fabanella boloniensis*, indicating Ostracod Assemblage 2.

Other occurrences. French and Swiss Jura: *G. praecursor* is the index species of the Lower Berriasian M1 charophyte Zone of Mojon (*in* Détraz and Mojon 1989), the base of which yields the Lower Berriasian marine ostracod *Protocythere revili* and palynofloras of Berriasian affinities.

Germany, Lower Saxony Basin: lower part of the Serpulit (Feist and Schudack 1991).

Globator protoincrassatus (Mojon) comb. nov.

Plate 1, figures 3–4, 8

1989 *Globator maillardi protoincrassatus* Mojon *in* Détraz and Mojon, p. 55, figs 5E–5L.
1991 *Globator maillardi protoincrassatus*; Mojon *et al.*, p. 502.

Holotype. Détraz and Mojon (1989, fig. 5E).

Emended diagnosis. Utricle of *Globator* composed of three units each comprised of one central basal cell, bearing three upper cells, flanked by two lateral basal cells each bearing an upper cell. Length of central basal cells equal to 29–30 per cent. of the utricle length. Upper cells slightly spiral, joining at the apex. Dimensions: 850–1150 μm long, 600–850 μm width. L/W ratio varying from 1·1 to 1·7.

Remarks. This form differs from *G. praecursor* by its shorter basal cells and more acute curvature of its upper cells, and from *G. maillardi* (Saporta) Grambast, by its larger basal cells and more twisted upper cells. The range of the new species is restricted to the Lower (not basal) Berriasian. The distinctive morphology and short stratigraphical range of Mojon's subspecies support it being raised to specific rank.

Distribution and range in southern England. Weald: Fairlight Borehole (293·2–293·5 m), Broadoak Calcareous Member, Lulworth Formation. Mojon identified *Cypridea dunkeri inversa* and *Fabanella boloniensis* from the same residue, indicating Ostracod Assemblage 2.

Dorset: Swanage, upper Soft Cockle Member, bed 70 of Clements (*in* Cope *et al.* 1969).

Other occurrences. French Jura: *G. protoincrassatus* is the index species of the Lower Berriasian M2 charophyte Zone of Mojon (*in* Détraz and Mojon 1989), dated by ammonites (in a marine intercalation) to the *Pseudosubplanites grandis* Zone, *P. grandis* Subzone (Clavel *et al.* 1986; Hoedemaeker 1991).

Germany: Lower Saxony Basin, upper part of the Serpulit (Feist and Schudak 1991).

Genus PERIMNESTE Harris, 1939

Perimneste horrida Harris, 1939

1939 *Perimneste horrida* Harris, p. 54, pls 13–15; pl. 16, figs 6, 8–9.

Distribution and range in southern England. According to Harris (1939) the species is common in the 'Middle' and 'Upper Purbeck Beds' of Dorset. The material of this species published by Harris and preserved at the Natural History Museum, London, comprises predominantly vegetative remains. Utricles are present at Durdle Door and Moigne Down.

Other occurrences. This species is common in the Berriasian of the Jura Mountains (Donze 1958; Mojon and Strasser 1987), Spain (Brenner 1976; Schudack 1987*a*) and Germany (Schudack 1990; Feist and Schudack 1991). It is unknown outside Europe.

Genus ATOPOCHARA Peck, 1938, emend. Peck, 1941

Atopochara triquetra (Grambast) comb. nov.

Plate 2, figure 9

1967 *Atopochara trivolvis* Peck, *pars*; Grambast, pl. 3, fig. 14.
1968 *Atopochara trivolvis triquetra* Grambast, p. 8, pl. 3, fig. 16.
1981 *Atopochara trivolvis* Peck *triquetra* Grambast; Musacchio, p. 474, pl. 5, fig. 9.
1981 *Atopochara trivolvis triquetra* Grambast; Zhang *et al.*, p. 153, pl. 1, figs 1–6.
1982 *Atopochara trivolvis triquetra* Grambast; Wang and Lu, p. 94, pl. 2, figs 9–13.
1982 *Atopochara trivolvis* Peck ssp.; Feist *in* Huckriede, p. 187, pl. 6, fig. 4.
1983 *Clypeator europeus* Grambast, *pars*; Kampmann, pl. 18, fig. 1a.
1985 *Atopochara trivolvis triquetra* Grambast; Jiang *et al.*, p. 166, pl. 1, fig. 1a–c
1986 *Atopochara trivolvis* subsp. *triquetra* Grambast; Martin-Closas and Grambast-Fessard, p. 38, pl. 8, figs 7–12.
1987*a* *Atopochara trivolvis triquetra* Grambast; Schudack, p. 135, pl. 6, figs 1–4.
1987*b* *Atopochara trivolvis triquetra* Grambast; Schudack, p. 16, pl. 2, figs 1–5.
1987 *Atopochara trivolvis* subsp. *triquetra* Grambast; Martin-Closas and Peybernes, p. 699, fig. 2:5–6.
1988 *Atopochara trivolvis triquetra* (Peck) Grambast; Mojon, pl. 2, figs a–e.
1989 *Atopochara trivolvis triquetra* Grambast; Schudack, p. 415, pl. 2, figs 1–6.
1991 *Atopochara trivolvis triquetra* Grambast; Lu and Yuan, p. 377, pl. 1, figs 3–6.

Holotype. C.633.16, Montpellier University (Grambast 1968, pl. 3, fig. 16).

Diagnosis. Utricle of *Atopochara*, composed of three basal cells, the two left hand ones bearing three upper cells and the right hand one bearing two upper cells and, in most cases, a slight antheridial cast. Upper cells twisted. Utricle subsurface visible between cells. Utricle showing a triangular and irregular outline when seen from apex or base. Dimensions of paratypes: utricle length, 656–924 μm; utricle width 632–973 μm; average cell number, 33; average antheridia number, 3; antheridium diameter, 73–218 μm.

Remarks. This form represents an evolutionary grade of the *Perimneste–Atopochara* lineage. During the sixty million years from the Berriasian to the Campanian, this lineage shows progressive evolution of the utricle with the condensation of the primarily ramified basal cells, the spiralization of the upper cells, and the regression and eventual disappearance of the antheridial casts, which are exceptionally preserved in *Perimneste*. *A. triquetra* is characterized by rather distinct basal branching (portions of the underlying layer being apparent), well spiralized upper cells, and a vestigial antheridial cell persisting in one branch. Two forms can be recognized. In the primitive form, the primary basal cells may be present and the characteristic antheridial sculpture still persistent; in the advanced form, the primary basal cells have disappeared and the ancestral antheridiae are represented only by short sterile cells with a smooth surface (Grambast 1967, 1974). In *A. trivolvis*, the utricle structure is quite condensed (the subsurface is no longer visible) and the lower right hand fork still shows a vestigial antheridium, but reduced to a spot without any structure. *A. triquetra* is a species with world-wide occurrences, ranging from Lower to Upper Barremian, *A. trivolvis* from Upper Barremian to Lower Aptian. It seems justified to raise *A. trivolvis triquetra*, which differs from *A. trivolvis* by distinct characters as well as by its range, to species rank.

Distribution and range in southern England (*primitive form*). Weald: Warlingham Borehole (430·0 m), lower part of the upper division of the Weald Clay, above Bed 3, associated with *Ascidiella iberica* and therefore considered to be Lower Barremian (see above; Feist and Grambast-Fessard 1991, p. 194, fig. 3*b*).

Distribution and range in southern England (*advanced form*). Isle of Wight: Cowleaze Chine, basal part of the Vectis Formation, attributed to the Upper Barremian.

Other occurrences (*primitive form*). Spain: Upper Hauterivian–Lower Barremian of Maestrazgo (Grambast 1968, 1974; Martin-Closas and Grambast-Fessard 1986; Martin-Closas and Salas 1988, 1989) and Cameros Basin (Schudack 1987*a*). The attribution to the Barremian is based on correlations of marginal non-marine Tethyan sequences with distal marine deposits dated by ammonites, nannofossils and planktonic foraminifers (Martin-Closas and Salas 1989).

Switzerland: a similar dating, based on palynology, was given by Mojon and Médus (1990) for specimens of *A. triquetra* primitive forms, albeit identified from thin sections in which the distinctive characteristics of the species do not appear clearly (cf. Mojon 1988, pl. 1, figs G–H).

Other occurrences (*advanced form*). Southern Jura: a recent report of this form in the succession of La Ruchére, dated by orbitoline foraminifers and palynofloras (Mojon 1988; Mojon and Médus 1990) is a new and important record, extending the known range of the San Carlos charophyte Zone of Grambast (1974), previously restricted to the Upper Barremian, into the Lower Aptian.

Spain: Maestrazgo, Upper Barremian–Aptian (Martin-Closas and Grambast-Fessard 1986; Martin-Closas and Salas 1989).

Other occurrences (*evolutionary stage not recorded*). Barremian of Germany (Schudack 1987*b*), Spain (Schudack 1987*a*, 1989), Argentina (Musacchio 1971, 1979) and China (Wang and Lu 1982; Jiang *et al.* 1985).

Subfamily CLAVATOROIDEAE Pia, 1927, emend. Grambast, 1969

Genus CLAVATOR Reid and Groves, 1916, emend. Harris, 1939

Clavator reidi Groves, 1924

Plate 1, figures 9–13

1916 *Clavator* Reid and Groves, p. 253, pl. 18.
1924 *Clavator reidi* Groves, p. 116.

Remarks. This species is well represented in the Purbeck Group of southern England. Among the Clavatoraceae, it represents an early stage of the *Flabellochara–Clypeator* lineage, first described by

Grambast (1974). *C. reidi* seems to be derived from *Nodosoclavator* by the intermediate of *C.* aff. *reidi*, the utricles of which present a bilateral symmetry but are not completely closed at the apex.

Distribution and range in southern England. Weald: Warlingham Borehole (612·3–614·8 m), Fairlight Borehole (273·7–274·0 m, 280·1–280·4 m and 281·0–281·3 m; *C.* aff. *reidi* at 296·0–296·3 m) and Broadoak Borehole (71·5–72·0 m). All occurrences in the upper part of the Broadoak Calcareous Member, Lulworth Formation.

Dorset: Durdle Door, just below the Cinder Bed Member, Lulworth Formation; Worbarrow Tout, just above the Cinder Bed, Durlston Formation; Swanage, Mammal Bed to 5 m above the Cinder Bed; Poxwell Road Cutting (NHM material).

Wiltshire: (identified with 'aff.') Swindon, exposure III of Sylvester-Bradley (1941); 'Swindon Series', Cythere Marls and Chara Marls.

Other occurrences. Switzerland: Bienne (Jura), Lower Berriasian Goldberg Formation (Häfeli 1966; Mojon and Strasser 1987).

France: Saint-Claude (Jura) and Marseille region, Purbeck Beds attributed to the Berriasian on ostracod evidence (Mojon 1989).

Spain: Maestrazgo, Berriasian beds dated by dasyclads (Canérot 1979).

Northern Portugal: ('*Clavator* cf. *reidi*'), Lower Cretaceous (Rey *et al.* 1968; Ramalho 1971).

Germany: Lower Saxony Basin, upper part of the Serpulit (Feist and Schudack 1991), attributed to the Berriasian by correlations with the M1b charophyte zone established in the French and Swiss Jura; these correlations are supported by ostracod and miospore evidence (Dörhöfer and Norris 1977; Détraz and Mojon 1989; Feist and Schudack, 1991).

Genus FLABELLOCHARA Grambast, 1959

Flabellochara grovesi (Harris) Grambast, 1962

Plate 1, figures 15–17

1939 *Clavator grovesi* Harris, p. 46, pl. 10, figs 1–12; pls 11–12; pl. 17, figs 8–13.
1962 *Flabellochara grovesi* (Harris) Grambast, p. 69.

Remarks. The specimens from Brouco (Portugal) attributed to *F. grovesi* (Ramalho 1971, pl. 33, fig. 6) have been reinterpreted by Schudack (1990) as *Clypeator discordis*, which co-occurs with *Globator rectispirale*. The beds in question, previously considered to be Lower Cretaceous, are now assigned to the Jurassic (Upper Tithonian). *F. grovesi* has not so far been recorded from Germany; published records of this species refer to *Clypeator discordis*.

Distribution and range in southern England. Weald: Fairlight Borehole (273·4–273·7 m and 280·1–280·4 m). The lowest occurrence is in the Robertsbridge faunicycle ('Lower' Purbeck), but nine faunicycles above the upper limit of *Cypridea dunkeri papulata*.

Dorset: 'Middle' and 'Upper Purbeck Beds' of Durdle Door, Worbarrow Tout, Mupe Bay and Poxwell Road Cutting (see Appendix 2).

Other occurrences. This species occurs in most of the classic 'Purbeck' successions attributed to the Berriasian. The species is restricted to the lower and middle Berriasian (Détraz and Mojon 1989).

Jura (France and Switzerland): Goldberg Formation and Mergel-und-Kalk-Zone (Häfeli 1966; Grambast 1970; Mojon and Strasser 1987; Détraz and Mojon 1989).

Spain: various areas and localities (Brenner 1976; Martin-Closas and Grambast-Fessard 1986; Schudack 1987*a*).

Sardinia: La Cala d'Inferno, Purbeck beds (Pecorini 1969; Colin *et al.* 1985).

Flabellochara xiangyunensis Wang *et al.*, 1976

Plate 1, figures 18–21

1976 *Flabellochara xiangyunensis* Wang *et al.*, p. 68, pl. 1, fig. 1

Remarks. This species has not previously been recorded outside China. Such wide distribution is not rare in charophytes, and other wide-ranging forms include the genera *Atopochara* (*A. trivolvis*, *A. triquetra*), *Peckisphaera* (*P. verticillata*) and *Clypeator* (*C. discordis*).

Distribution and range in southern England. Weald: Wadhurst Park No. 3 Borehole (6·7–7·6 m), Glynleigh Borehole (59·0–59·5 m) and Kitchenham Dam Borehole (281·3 m). All occurrences are in the Wadhurst Clay.

Other occurrences. Yunnan Province, China: Valanginian (Wang *et al.* 1976; Wang and Lu 1982).

Genus CLYPEATOR Grambast, 1962, emend., 1970

Clypeator combei Grambast, 1970

Plate 2, figure 4

1970 *Clypeator combei* Grambast, p. 1967, pl. 3, figs 1–5.

Remarks. From the records presented here, the range of *C. combei*, previously reported only from the Lower Barremian, extends from Upper Hauterivian into the Upper Barremian.

Distribution and range in southern England. Weald: Warlingham (430·4 m), Ripe (159·5–160·0 m) and Hailsham (29·5–30·0 m) boreholes. This species occurs in the beds above the main occurrences of Small-'*Paludina*', below (Ripe, Hailsham) and above (Warlingham) Bed 3 of the Weald Clay (Lake and Young 1978; Worssam 1978). The borehole records range from Upper Hanterivian to Lower Barremian.

Isle of Wight: Cowleaze Chine, in the basal part of the Vectis Formation (Upper Barremian).

Other occurrences. Spain: Maestrazgo, 'Lower Barremian' (Grambast 1970, 1974; Martin-Closas and Salas 1989). The attribution to Lower Barremian was by Grambast (1974), probably on the basis of charophyte evolutionary stages.

Clypeator britannicus sp. nov.

Plate 2, figures 7–8

Holotype. MPK 8906, British Geological Survey, Keyworth (Pl. 2, fig. 8).

Paratype. MPK 8905 (Pl. 2, fig. 7).

Type horizon and locality. Grinstead Clay (Valanginian), Kingsclere Borehole, Hampshire; 306·6 m (holotype) and 305·7 m (paratype).

Diagnosis. Utricle of *Clypeator* characterized by the position of the lateral pores in the lower third of the utricle length, the lateral shields being composed of ten to eleven triangular cells radiating from the lateral pores. Dimensions: length varying from 475 to 625 μm, width from 500 to 625 μm. L/W ratio varying from 0·9 to 1·1.

Remarks. The *Clypeator* phylogenetic lineage (Grambast 1970) is characterized by the development of intermediate cells between the basal and upper cells. The new species represents a new grade, intermediate between the Berriasian *Clypeator discordis* and the Hauterivian–Barremian *C. combei*. In the new species, the lateral pores are in the lower third of the length of the utricle, as they are in *C. discordis*, but in the latter the intermediate and basal cells are approximately of the same size and rectangular shape. In contrast, *C. britannicus* has intermediate cells which resemble the upper ones, and which are elongated and slightly undulated. By this character, the new species resembles *C. combei*, but differs from it in the low position of the lateral pores.

Distribution and range in southern England. Hampshire: so far recognized only from its type locality (see above).

Clypeator discordis Shaikin, 1976

Plate 2, figures 5–6

1970 *Clypeator* sp. Grambast, p. 1965, pl. 1, fig. 3.
1976 *Clypeator discordis* Shaikin, p. 82, figs 9–10.

Distribution and range in southern England. Wiltshire: Town Gardens Quarry, Swindon. In the succession established by Sylvester-Bradley (1941), the species ranges through the major part of the Purbeck sequence; in its lowest occurrence, in the Lower Pebbly Beds, it is associated with ostracods of the Quainton–Stair faunicycles (I. P. Wilkinson in litt. 1991). Using Anderson's (1985) ostracod evidence, these faunicycles, which constitute ostracod Assemblage 1, are older than the Swindon faunicycle which, in the Fairlight Borehole, contains the (inferred) Tithonian *Globator rectispirale*. *C. discordis* thus appears in the Upper Jurassic.

Other occurrences. Portugal: Brouco section. The specimen, named *Flabellochara grovesi* and figured by Ramalho (1971, pl. 33, fig. 6), has been re-identified as *Clypeator discordis* (Schudack 1990). The attribution of the Brouco section to the Tithonian on the occurrence of *Globator rectispirale* (see above) confirms that the first appearance of *C. discordis* is in the Upper Jurassic.

This species is common in the Berriasian of Europe (see Schudack 1987*a*, 1990; Feist and Schudack 1991). It has also been reported from the Valanginian of Sichuan Province, China (Huang 1985) and from the Hauterivian and Barremian of the Pre-Dobrogean Depression in Ukraine (Shaikin 1976).

EXPLANATION OF PLATE 2

Figs 1–3. *Triclypella calcitrapa* Grambast. Ripe Borehole, Sussex, 154·00–154·50 m; Weald Clay. 1, MPK 8901; lateral view, showing one of the three faces with central pore. 2, MPK 8922; basal view, showing the triradiate symmetry of the utricle. 3, MPK 8923; dorsal (adaxial) face, showing the high position of the lateral pores. All × 45.

Fig. 4. *Clypeator combei* Grambast. MPK 8902; Ripe Borehole, 154·00–154·50 m; Weald Clay; lateral view, showing one of the two faces of the utricle; × 45.

Figs 5–6. *Clypeator discordis* Shaikin. Town Garden Quarry, Swindon; Lower Pebbly Beds; lateral views, showing the basal cell subdivided; × 60.

Figs 7–8. *C. britannicus* sp. nov. Kingsclere Borehole, Hampshire, 306·6 m; ?Grinstead Clay equivalent. 7, MPK 8905, paratype; dorsal view, showing the low position of the lateral pores; × 45. 8, MPK 8906, holotype; lateral view, showing lateral pore and short basal cell; × 48.

Fig. 9. *Atopochara triquetra* Grambast, advanced form. CF 2777a-7; Cowleaze Chine, Isle of Wight; lower Vectis Formation; × 43.

Fig. 10. *Ascidiella iberica* Grambast. MPK 8907; Warlingham Borehole, Sussex, 430·0 m; Weald Clay, upper part; lateral view; × 25.

Figs 11–16. *Sphaerochara andersoni* sp. nov. Ripe Borehole, Sussex, 154·00–154·50 m; Weald Clay. 11, MPK 8908, holotype; lateral view; × 60. 12, MPK 8909, paratype; lateral view; × 48. 13, MPK 8910, paratype; lateral view; × 45. 14, MPK 8911, paratype; apical view of a germinated specimen; × 45. 15, MPK 8912, paratype; basal view; × 42. 16, MPK 8913, paratype; apical view; × 45.

Fig. 17. *Latochara* sp. A. CF 2792b-1; Town Gardens Quarry, Swindon; Upper Marlstones; lateral view; × 45.

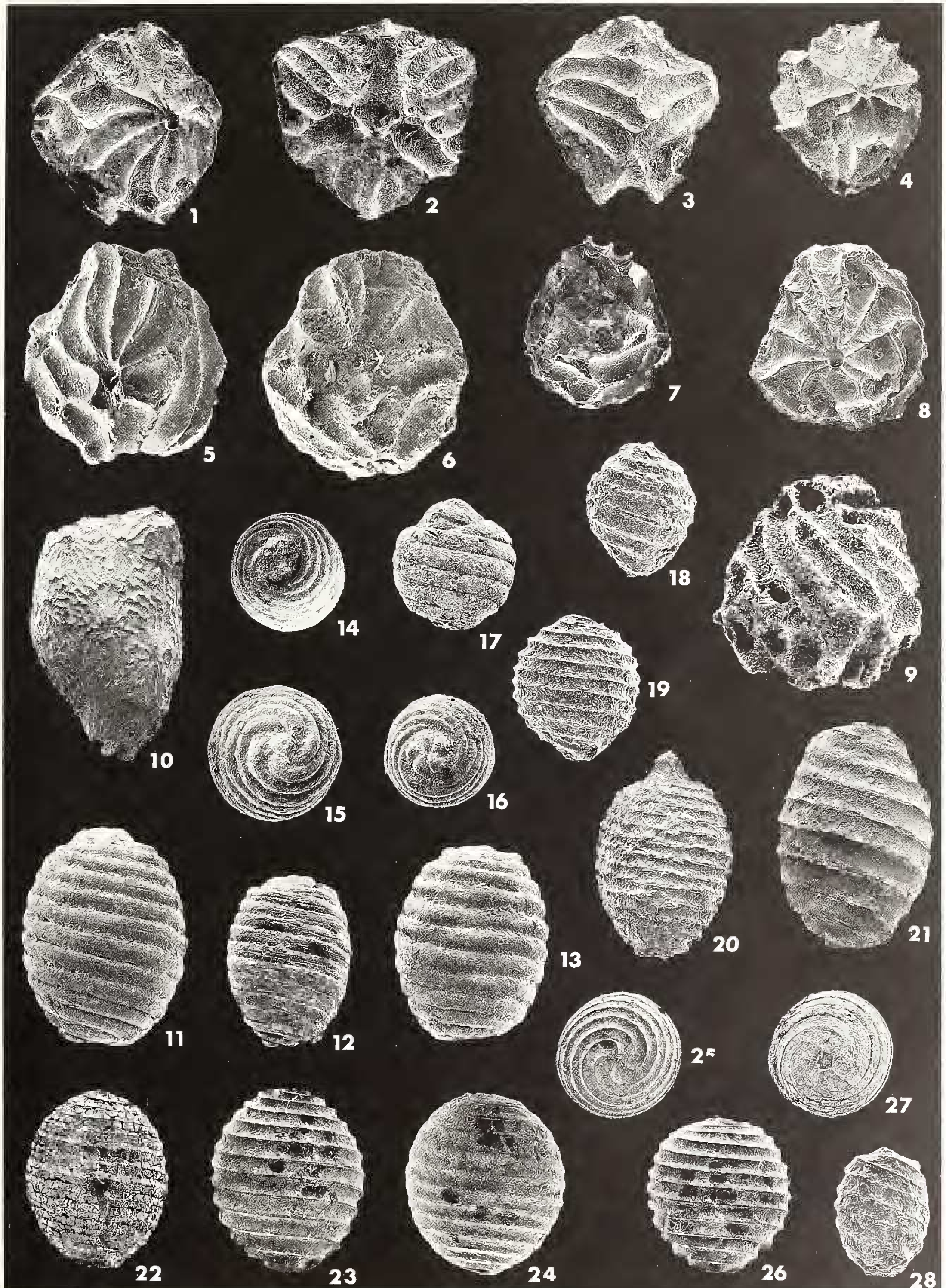
Figs 18–19. *Mesochara* sp. A. Fairlight Borehole, Sussex, 281·0–281·3 m; Broadoak Calcareous Member; lateral views. 18, MPK 8914. 19, MPK 8915. Both × 70.

Fig. 20. *Latochara* sp. B. MPK 8916; Warlingham Borehole, Sussex, 581·7 m; Greys Limestones Member; lateral view; × 66.

Fig. 21. *Porochara maxima* Donze. MPK 8917; Warlingham Borehole, Sussex, 612·1 m; Arenaceous Beds Member; lateral view; × 48.

Figs 22–27. *Peckispharea verticillata* Peck. Cowleaze Chine, Isle of Wight; lower Vectis Formation. 22–24, 26, CF 2777a 1 to a3, a4; lateral views; 25, CF 2777a-5; apical view. 27, CF 2777a-6; basal view. All × 45.

Fig. 28. *Aclistochara* sp. A. MPK 8918; Warlingham Borehole, Sussex, 614·2 m; Broadoak Calcareous Member, lateral view; × 70.



FEIST *et al.*, charophytes

Genus TRICLYPELLA Grambast, 1969

Triclypella calcitrapa Grambast, 1969

Plate 2, figures 1–3

1969 *Triclypella calcitrapa* Grambast, p. 881, pl. 1, figs 1–7.

Distribution and range in southern England. Weald: this species is commonly associated with *C. combei* in the beds above the Small-'*Paludina*' Limestone beds of the Weald Clay of the Weald. In the Ripe Borehole, the species occurs in beds at 154·0 to 154·5 m, dated palynologically as Hauterivian (Feist and Batten 1990). It also occurs in equivalent beds in the Hailsham Borehole (Text-fig. 2). In the Warlingham Borehole, it occurs at 430·0–430·7 m; in the sample from 430·0 m, it co-occurs with *Ascidiella iberica*, which is considered to be lower Barremian. The species has not been recorded from the topmost Wealden Beds Vectis Formation of the Isle of Wight; its range thus seems restricted to the highest Hauterivian–Lower Barremian.

Other occurrences. Spain: north-central and eastern Spain, 'Lower' (but not 'basal') Barremian (Grambast 1970, 1974; Schudack 1987*a*; Martin-Closas and Salas 1989). The species ranges from the Hauterivian to the Barremian (Wang and Lu 1982).

Genus ASCIDIELLA Grambast, 1966

Ascidiella iberica Grambast, 1966

Plate 2, figure 10

1966 *Ascidiella iberica* Grambast, p. 2210, pl. 1, figs 1–6.

Distribution and range in southern England. Weald: the species was found only in the Warlingham Borehole (430·0 m), in a sample from above Bed 3 of the Weald Clay, which is considered to be Lower Barremian from its position 1·4 m above the lowest horizon dated by angiosperm pollen (Hughes and McDougall 1990, fig. 3) and dinocysts (Harding 1990) as Barremian.

Other occurrences. Spain: eastern Maestrazgo (Combes *et al.* 1966), above beds containing Hauterivian–Barremian foraminifers; Cameros Basin (Schudak 1987*a*), above beds with ostracods indicating the same age. Although considered to be of early Barremian age, it is therefore possible that the species ranges down into the upper Hauterivian.

Family CHARACEAE, Agardh, 1824
Subfamily CHAROIDEAE Al. Braun *apud* Migula, 1897
Genus PECKISPHAERA Grambast, 1962

Peckisphaera verticillata (Peck) Grambast, 1962

Plate 2, figures 22–27

1937 *Chara verticillata* Peck, p. 84, pl. 14, figs 30–33
1962 *Peckisphaera verticillata* (Peck) Grambast, p. 78.

Distribution and range in southern England. Isle of Wight; Cowleaze Chine, the fossiliferous bed at the base of the Vectis Formation (attributed to the Upper Barremian – see below).

Other occurrences. USA: Rocky Mountains, common in the Upper Jurassic and Lower Cretaceous (Peck 1957).

East Asia: China, Triassic (Jiang *et al.* 1985; Lu and Luo 1990); Mongolia, Upper Cretaceous (Karczewska and Ziembinska-Tworzydlo 1970).

Spain: Barremian (Schudack 1987*a*, 1990).

Subfamily NITELLOIDEAE Al. Braun *apud* Migula, 1897

Genus SPHAEROCHARA Mädler, 1952, emend. Horn af Rantzien and Grambast, 1962

Sphaerochara andersoni sp. nov.

Plate 2, figures 11–16

Holotype. MPK 8908, British Geological Survey, Keyworth (Pl. 2, fig. 11).

Paratypes. MPK 8909-8913 (Pl. 2, figs 12–16).

Type horizon and locality. Weald Clay, Hauterivian, Ripe Borehole, Sussex, 154·0–154·5 m.

Derivation of name. The species is dedicated to the late Dr F. W. Anderson, in token of gratitude for having preserved numerous charophyte specimens during his work on the Purbeck and Wealden ostracods of southern England.

Diagnosis. Gyrogonite of *Sphaerochara*, characterized by its ellipsoid to cylindroid shape, the length–width ratio varying from 1·1 to 1·5. Lower part of the basal plate superficial, bearing a central nodule. Dimensions: length 425–600 μm, width 375–525 μm. Eleven to twelve circumvolutions seen in lateral views.

Remarks. By its prominent apical rosette and its thick basal plate, superficial at the basal pore level, the new species clearly belongs to *Sphaerochara*. It differs from other species assigned to that genus by its elongated, instead of, the more common, spherical shape. In this character, *S. andersoni* resembles *S. bicarinata* Yang from the Minhe Formation of north-west China (Hao *et al.* 1983), but this latter species is significantly smaller.

Distribution and range in southern England. Weald: Warlingham Borehole (430·0 m, 430·4 m and 430·7 m), Ripe Borehole (154·0–154·5 m) and Hailsham Borehole (16·50–17·99 m). All these occurrences are in the lower portion of the upper Weald Clay. Forms resembling *S. andersoni* (assigned here to *S.* aff. *andersoni*) but with a more globular shape, are present in the Wadhurst Clay, in the Wadhurst Park No. 3 Borehole (59·0–59·5 m), and the Robertsbridge Borehole, Sussex (12·2–12·3 m).

Hampshire: Kingsclere Borehole (306·6 m), Grinstead Clay.

SUCCESSION OF THE CHAROPHYTE ASSEMBLAGES AND BIOSTRATIGRAPHICAL IMPLICATIONS

Charophytes occur intermittently in the Purbeck and Wealden successions of southern England; on the whole, each standard stage can be characterized by a particular assemblage, but abundance, preservation and diversity vary throughout the succession. The abundant and diverse Purbeck floras enable a biozonation to be established for the Jurassic–Cretaceous transition but other intervals, such as the detritic, and/or marine and weakly calcareous deposits either do not contain charophytes or contain only poorly calcified specimens without stratigraphical significance. We have considered as undefined zones, or as interregna, these intervals which, however, are well documented elsewhere and thus permit an appraisal of the entire Upper Jurassic–Lower Cretaceous charophyte zonation. The local charophyte zones introduced here are based on the first occurrences of successive index-species in the succession. The index species are chosen from the best dated and most widely distributed species of the assemblages. An 'interregnum' represents the time-interval between the last occurrence of the index species of the previous zone and the first occurrence of the index species of the following one.

PURBECK LIMESTONE GROUP

Stratigraphy

The Purbeck Limestone Group of southern England constitutes a predominantly non-marine succession of limestones and mudstones spanning the Jurassic–Cretaceous boundary. This sequence rests on marine sediments (Portland Group) of late, but not latest, Jurassic age. It is found in two main depositional areas, a Western or Wessex Basin to the west of the Portsdown structure and an Eastern or Wealden Basin to the east of this structure (Anderson 1985, fig. 1).

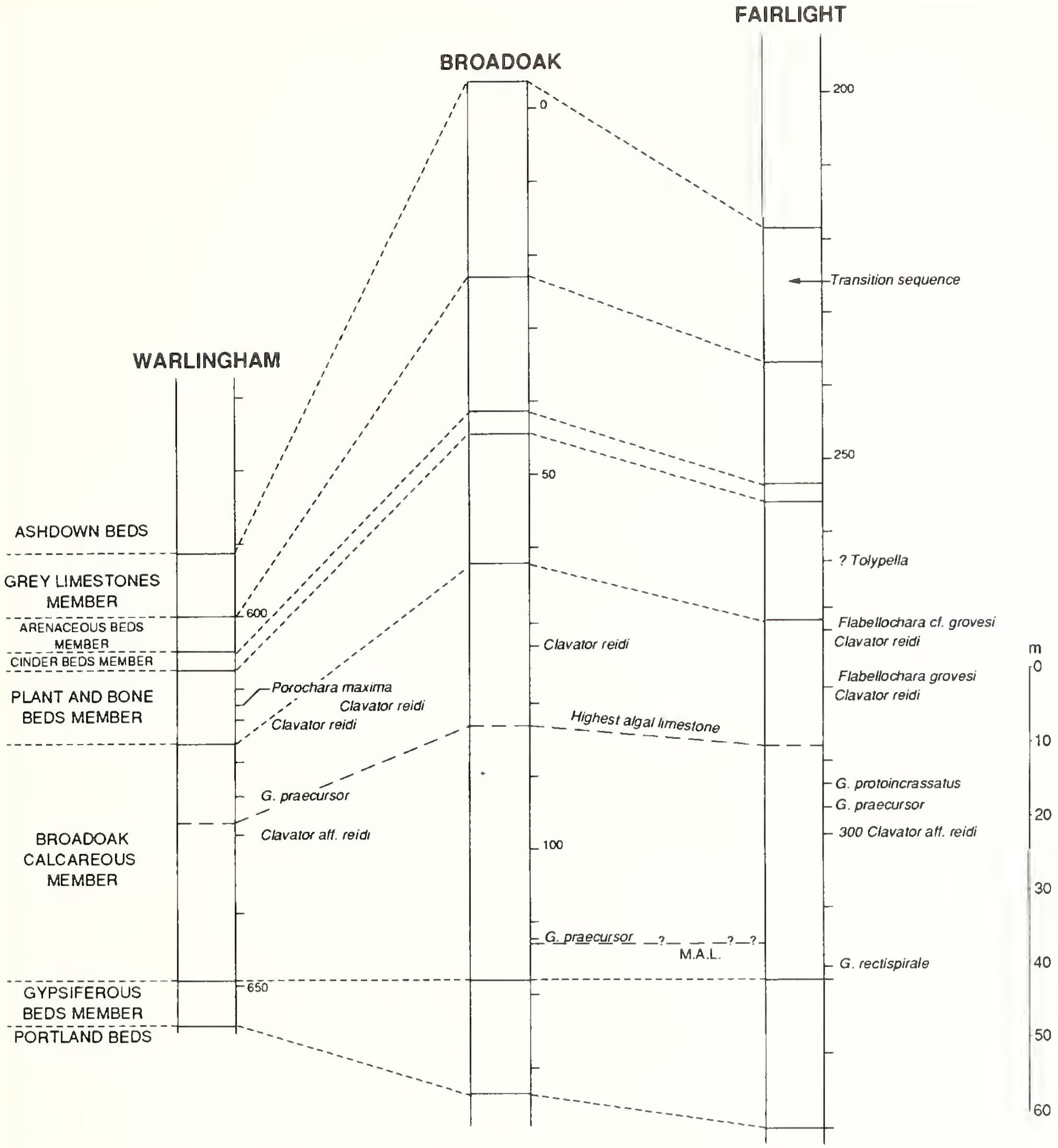
Wessex Basin. The stratotype is the section in Durlston Bay, Swanage (Melville and Freshney 1982, fig. 16), where the group attains its maximum thickness (House 1989, table 7) and, except for the basal and topmost beds, is superbly exposed (for section details see Clements *in* Cope *et al.* 1969; Clements 1993). The junction in the Isle of Purbeck between the 'Purbeck Beds' as originally defined and the overlying Wealden Beds (Supergroup) is gradational (Strahan 1898; Arkell 1947*a*, p. 148); recent research has shown that the base of the type Wealden Beds as recognized in the Wealden Basin must be located *within* rather than at the top of the Purbeck sequence (Morter 1984; Lake and Shephard-Thorn 1987).

Following Clements (1993) and standard British Geological Survey (BGS) practice, two formations are recognized in the stratotype Purbeck Limestone Group in this paper, the Lulworth and Durlston formations (Townson 1975) in ascending order, with the base of the latter being taken at the base of the near-marine Cinder Bed Member. The succession was earlier divided informally into the now redundant lower, middle and upper Purbeck Beds (Forbes 1851), which were used, extensively, both in this country and abroad, until comparatively recently (e.g. Anderson 1985).

Within each of the original three subdivisions, distinctive groups of beds were recognized and named, based on a combination of their lithological character and fossil content. These groups of beds have member status (Clements 1993) within the two component formations. The Cherty Freshwater Member near the top of the Lulworth Formation is the source of much of the well-preserved Purbeck charophyte material described by Harris (1939), notably *Flabellochara grovesi* and *Perimneste horrida*.

Wealden Basin. In the Wealden Basin, the Purbeck strata crop out in three faulted inliers, where the gypsiferous basal beds have been exploited for gypsum; they have also been penetrated by several deep cored boreholes (for details see Lake and Shephard-Thorn 1987). The occurrence of a shell-rich unit (Cinder Bed Member, Text-Fig. 1), characterized by oysters, and the near-marine '*Protocardia*' *major* molluscan association (Morter 1984) allows the succession to be subdivided into the same two formations (Lulworth and Durlston) recognized in the Wessex Basin, although the member nomenclature adopted is different (Lake and Shephard-Thorn 1987, table 3). Charophytes indicating a Berriasian age for the Broadoak Calcareous Member of the Lulworth Formation have already been reported by Feist (*in* Lake *et al.* 1987) and are further discussed later in this paper. Near the base of this member there is a marker horizon of local importance, the Mountfield Adit Limestone, also referred to later in the text.

The succession of lithologies and inferred depositional environments of the Purbeck Group in the Wealden Basin, however defined, is essentially comparable with that found in the Wessex Basin (Worssam and Ivimey-Cook 1984 and references therein; Anderson 1985, p. 3, fig. 5). The two successions are generally held to be at least broadly correlative and contemporaneous, despite somewhat controversial palynological evidence to the contrary (Wimbledon and Hunt 1983; Hunt 1985, 1987; Norris 1985), which suggests that the base of the Purbeck succession is significantly younger in the southern Weald (Brightling Mine, Fairlight Borehole) than it is in Dorset. Batten (pers. comm. 1992) emphasizes the geographical proximity between Dorset and the Weald at the time, and also the fact that there is good evidence for a more or less synchronous climatic change from arid to humid throughout that part of Europe. He considers that the differences in palynological assemblages between apparently lithostratigraphically correlative successions may



TEXT-FIG. 1. Lithofacies correlation between Warlingham, Broadoak and Fairlight boreholes, modified after Morter (1984), showing key charophyte records. M.A.L., tentative position of Mountfield Adit Limestone.

result from a more hostile environment in Dorset compared with the Weald. Allen and Wimbledon (1991) noted that the same sequence of events (*Classopollis* pollen decline, *Cypridea posticalis* occurrence, quasi-marine Cinder Bed and percentage increase in the kaolinite component of the clay mineral assemblages) can be recognized in both areas, which suggests that the base of the Purbeck is not diachronous.

Marginal areas. Purbeck strata are also found in marginal areas relative to the two main depositional basins, namely in Wiltshire in the Vale of Wardour and in three outliers near Swindon

(Sylvester-Bradley 1941; Arkell 1947*a*, 1947*b*, 1948; Wimbledon 1976), as well as in outliers in Oxfordshire and near Aylesbury, Buckinghamshire (Barker 1966; Bristow 1968; Wimbledon 1980; Radley 1992). The correlation between the Swindon and Aylesbury successions and the Dorset stratotype remains uncertain (see Barker *et al.* 1975; Morter 1984), but Anderson (*in* Worssam and Ivimey-Cook 1971) considered that at least the lower part of the Swindon Purbeck succession predates the Purbeck stratotype and correlates with the higher part of the Portland Stone Formation. Of the marginal localities, only the Swindon succession is considered in this paper. The Purbeck succession cored in the Kingsclere Borehole in the western part of the Wealden Basin exhibits a succession intermediate between that of the Dorset stratotype and that of the marginal developments near Aylesbury.

The Purbeck Limestone Formation succession at Swindon. In the classic Great (now Town Gardens) Quarry near Swindon, a complex succession of marls, limestones and pebble-beds (including at least one limestone with marine fossils), the so-called 'Swindon Series' (Keeping 1883), rests with an erosional contact on the Swindon Sand and Stone Member of the Portland Stone Formation. Stratigraphical details of the sections then exposed, together with an extensive review of previous measured sections, were given by Sylvester-Bradley (1941) and later summarized by Arkell (1947*b*, 1948). The bed nomenclature used in this paper follows that introduced by Sylvester-Bradley, his bed numbers being given in parentheses after the bed names.

The basal 2 m of the 'Swindon Series', comprising a basal pebble bed [Lower Pebble Bed (2)], a marlstone unit [Lower Marlstones (3)], an ostracod-rich marl [Cythere Marl (4)] and terminating in a limestone with marine bivalves and gastropods [Swindon Roach (5)] were separated by Wimbledon (1976) as the Town Gardens Member and assigned to the top of the Portland Stone Formation. The overlying 10 m succession was assigned to the Purbeck Limestone Formation. This succession comprises two units of marlstones [Middle (6) and Upper (8) Marlstones] alternating with units of sandy marls with well-preserved freshwater ostracods and reworked limestone pebbles [Middle Pebbly Bed (7) and Upper Pebbly Beds (9)], these being overlain by two limestones [Boxy Tufa (10) and Swindon Flags (12)] with an intercalated unit of earthy marls [Chara Marls (11)] containing abundant ostracods and charophytes. Arkell (1948, p. 202) recorded an additional unit overlying the Swindon Flags consisting of marl with limestone rubble, which had not been noted previously.

In the present study, charophyte assemblages have been examined from the Lower Pebbly Bed, Cythere Marl, Middle Pebbly Bed, Upper Pebbly Beds and Chara Marls. The identification of the taxa present and the biostratigraphical interpretations arising therefrom differ significantly from those published by Harris (1939; *in* Sylvester-Bradley 1941).

Charophyte succession

The most representative succession of charophyte occurrences was found in borehole samples from the Weald. In contrast, on the Dorset coast, only the beds of the uppermost Lulworth Formation to the lowest Durlston Formation have yielded charophytes.

In the Fairlight Borehole, the Broadoak Calcareous Member can be subdivided into three local zones, based on the first occurrences of the successive chronological species of *Globator*; the succeeding beds are referred to a fourth zone. As discussed below, the Jurassic–Cretaceous boundary lies between local charophyte zones 1 and 2.

Zone 1. This is defined as the interval between the first occurrences of *Globator rectispirale* and *G. praecursor*; the zone is represented in the lowest part of the Broadoak Calcareous Member (Lake and Holliday 1978) which appears in the Fairlight Borehole and may be provisionally interpolated in the Warlingham and Broadoak boreholes, below the occurrences of *G. praecursor*. The only occurrence of *G. rectispirale* is at 317·6–317·9 m in the Fairlight Borehole. An important additional species is *Clavator* aff. *reidi* (utricles incompletely constituted).

By direct correlation, Zone 1 (as recognized in the Fairlight Borehole) corresponds to the lower part of the Swindon ostracod faunicycle of Assemblage 2 of Anderson (1975). The Swindon succession, which is referable to the underlying Assemblage 1, is provisionally included in the charophyte Zone 1, albeit in the absence of *Globator praecursor* (see below).

Outside southern England, the zone is identifiable by the occurrence of *G. rectispirale* in the Seba Mahjouba Formation of the Chellala Mountains (Algeria), 50 m below beds referred to the Upper Tithonian A2–A3 calpionellid Zone (Benest 1981), which is correlated with the Late Tithonian '*Durangites*' ammonite Zone. The lower part of the Portuguese 'Infravalanginian' (Rey *et al.* 1968; Ramalho 1971) which has yielded *G. rectispirale* and *Clypeator discordis* may be equivalent to this zone. Rey (in litt. 1991) considers that these beds should now be attributed to the Upper Jurassic (Tithonian).

In terms of ammonite zones, the basal part of the Broadoak Calcareous Member, which is the stratotype of the charophyte local Zone 1, has been inferred to correlate with the *Titanites anguiformis* Zone (Wimbledon 1980 and this paper). Charophytes thus indirectly confirm the Boreal–Tethyan correlations of the *anguiformis* and '*Durangites*' ammonite zones.

Zone 2. This is defined as the interval between the first occurrences of *Globator praecursor* and *G. protoincrassatus*; the zone is found represented in the lower–middle part of the Broadoak Calcareous Member. The lowest occurrences of *G. praecursor* are at 296·0–296·3 m in the Fairlight Borehole, at 625·3 m in the Warlingham Borehole, at 111·50–112·00 m in the Broadoak Borehole and at 270·6 m in the Brightling No. 27 Borehole. An important additional species is *Clavator reidi*.

By direct correlation, Zone 2 (as recognized in the Fairlight Borehole) corresponds to the ostracod faunicycles between Swindon (*pars*) and the upper part of the Lower Soft Cockle (Anderson 1975). Outside the British Isles, Zone 2 corresponds approximately to the M1 charophyte Zone defined by Détraz and Mojon (1989) in the Jura Mountains and referred to the basal Berriasian. Zone 2 is also identifiable in the lower part of the Serpulit of the Lower Saxony Basin (Schudack 1991; Feist and Schudack 1991).

Zone *3*. This is defined as the interval between the first occurrences of *Globator protoincrassatus* and *Flabellochara grovesi*; the zone is identified in the upper part of the Broadoak Calcareous Member (Lake and Holliday 1978); the former species occurs in the Fairlight Borehole at 293·2–293·5 m depth. An important additional species is *Clavator reidi* (primitive and advanced forms).

Zone 3 is directly correlated with the Lower Soft Cockle (upper part), Upper Soft Cockle, Penshurst and Ringstead ostracod faunicycles. The zone is recognized by the occurrence of *G. protoincrassatus* in the topmost Soft Cockle Member of Dorset (Bed 70 of Clements *in* Cope *et al.* 1969; Clements 1993). Outside southern England, Zone 3 corresponds to the Lower Berriasian M2 charophyte zone defined by Détraz and Mojon (1989) in Switzerland, dated by ammonites of the *Pseudosubplanites grandis* Zone (Clavel *et al.* 1986; Hoedemaeker 1991). Zone 3 is also identifiable in the upper part of the Serpulit of the Lower Saxony Basin (Feist and Schudack 1991).

Zone 4. This is defined as the interval between the first occurrence of *Flabellochara grovesi* and the last occurrence of *Clavator reidi*. The zone spans the highest Broadoak Calcareous Member, the Plant and Bone Beds, Cinder Bed, Arenaceous Beds and Greys Limestones members (Lake and Holliday 1978). The lowest record of *Flabellochara grovesi* is at 281·0–281·3 m in the Fairlight Borehole. Important additional species are *Porochara maxima*, *Perimneste horrida* and *Clavator reidi*.

The base of Zone 4 in the Fairlight Borehole is directly correlatable with the Robertsbridge ostracod faunicycle of Anderson (1975). In Dorset, the lowest occurrence of this zone is identifiable in the Cherty Freshwater Member; its upper part includes the Cinder Bed [Member] which is correlated with the *Praetollia runctoni* ammonite Zone (Casey 1973).

WEALDEN SUPERGROUP

Stratigraphy

The Wealden Supergroup (Series) in the type area consists of two broad subdivisions, the Hastings Beds below and the Weald Clay above. The former comprises an alternating sequence of formations (and locally members) which are dominantly argillaceous or of variable grain-size but with a significant arenaceous content (Ashdown Beds–Upper Tunbridge Wells Sand; cf. Text-Fig. 3). Whilst the clay subdivisions are thought to represent lacustrine/lagoonal environments, the intervening 'sands' show fluvial/alluvial associations. In the Hastings Beds, important transgressive events are recognized at the bases of the Wadhurst Clay and the Grinstead Clay and the major facies-change below the Weald Clay may reflect another of more regional significance (Allen and Wimbledon 1991).

The Wealden Group of the Wessex Basin is generally poorly understood. The Wessex Formation, of alluvial/fluvial facies with few known lithostratigraphical or faunal markers, comprises sandstones and variegated mudstones (Hesselbo and Allen 1991). The Hauterivian–Barremian boundary has been placed approximately at the levels of the 'Pine Raft' of the Isle of Wight and of the 'Coarse Quartz Grit' of Dorset, on palynological evidence (Hughes and McDougall 1989). On the Isle of Wight, the Wessex Formation is succeeded by the lagoonal Vectis Formation, grey shelly mudstones, which has been correlated with the upper part of the Weald Clay (Anderson 1967; Stewart 1981).

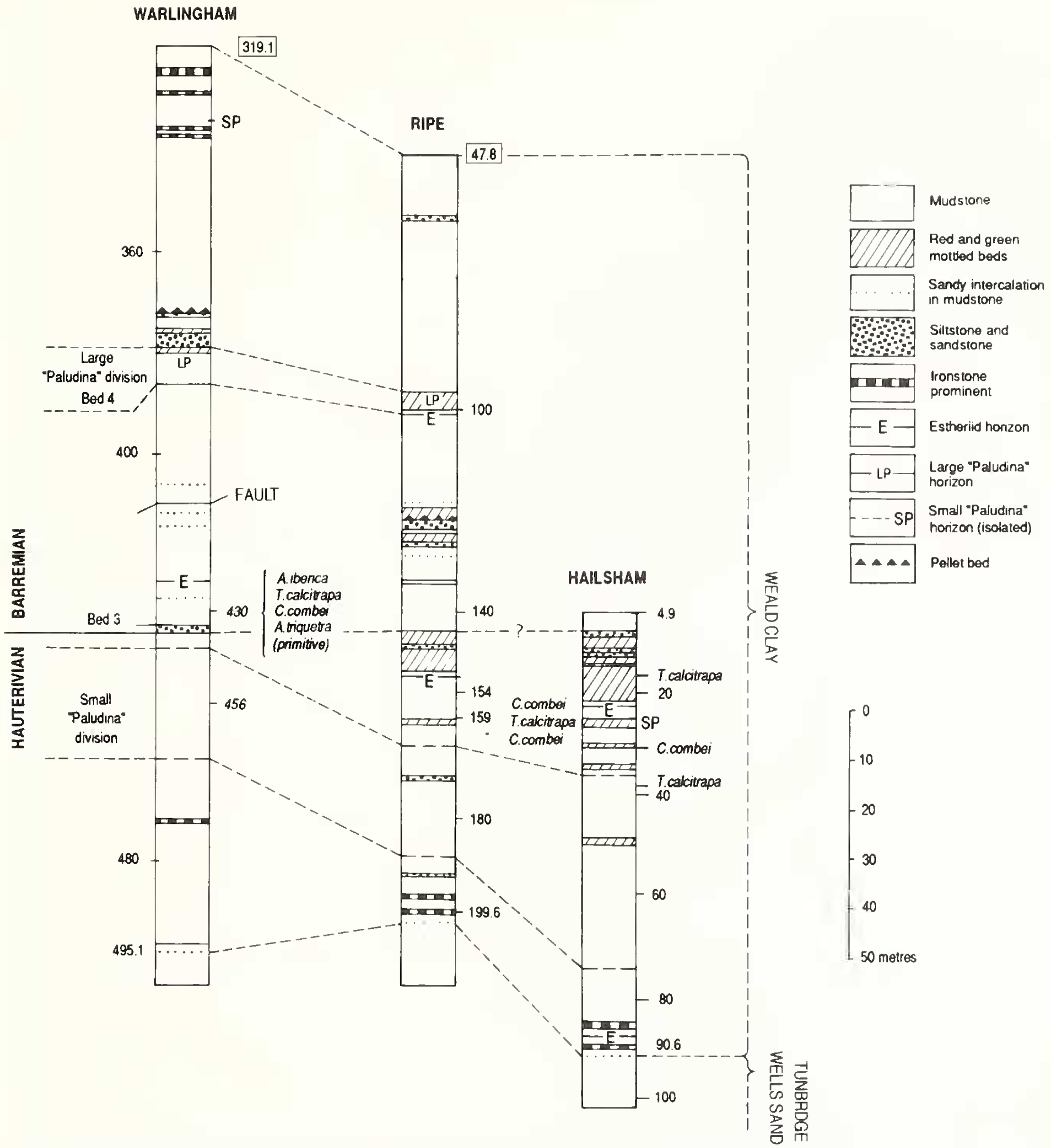
The Kingsclere (Hants) Borehole (National Grid Reference SU 4984 5820) (discussed later) apparently encountered red mottled beds of Wessex Formation facies overlying grey beds of Wealden aspect, but the effect of the sub-Aptian unconformity above is unclear. One possibility is that the variegated beds may reflect an expansion of those seen in the highest Hastings Beds and Weald Clay at outcrop (mid-Tunbridge Wells Sand-equivalent and above). Hughes *et al.* (1979) recognized Barremian palynomorphs in the highest part of the sequence at Kingsclere.

Subdivision of the Weald Clay

The scheme of subdivision adopted here follows that developed in the southern outcrop (Lake and Young 1978; Lake *et al.* 1987; Young and Lake 1988), following the work of Topley (1875, p. 102) and Thurrell *et al.* (1968, p. 24). The lithological marker horizons recognized within the dominantly clay sequence are as follows:

7 Sandstone(s)
6 Large-'*Paludina*' limestone
5 Sandstone(s)
4 Large-'*Paludina*' limestone
3 Sandstone(s)
2 Small-'*Paludina*' limestones and '*Cyrena*' limestones
1 Horsham Stone

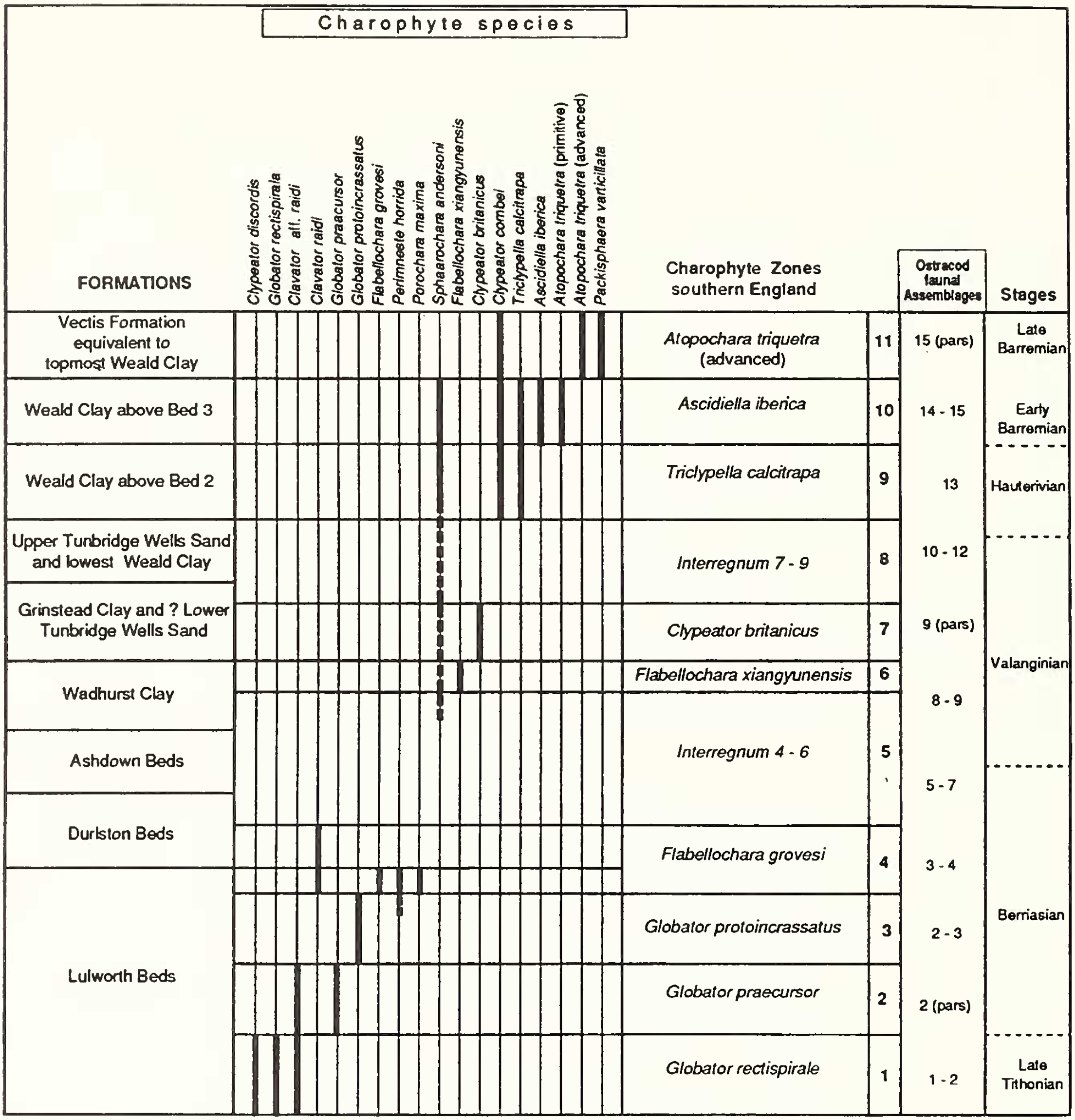
The Large-'*Paludina*' limestone units are individually restricted in vertical range, but the other horizons may comprise more than one intercalation within the sequence. For example, Bed 2 (clays with Small-'*Paludina*' limestones and '*Cyrena*' limestones) was found to have only a broad 'zonal' equivalence (Text-Fig. 2). Bed 4 (the lower of two commonly occurring Large-'*Paludina*' limestones) was, however, shown to be characterized by the ostracod *Cypridea bogdenensis* in the Gillmans faunicycle and therefore forms a useful marker horizon. In the Warlingham Borehole, Worssam and Ivimey-Cook (1971) attributed to 'Topley's Bed 5' a complex tripartite succession comprising, in ascending order: (a) 2·1 m of glauconitic sandstones with a brackish-marine molluscan fauna; (b) 0·8 m of shaly mudstones containing a bed of glauconitic sand with quartz pebbles; (c) 4·3 m of sediments of terrestrial to freshwater aspect containing, in the basal metre, rootlet beds, *Unio* and charophytes. A sample (431·4 m) from above the pebble bed in unit b yielded Barremian angiosperm pollen (Hughes and MacDougall 1990) and dinocysts (Harding 1990); the



TEXT-FIG. 2. Lithofacies correlation between the Warlingham, Ripe and Hailsham boreholes in the Weald Clay, modified after Lake and Young (1978), showing key charophyte records.

charophytes at the base of unit c are thus demonstrably Barremian. The Hauterivian–Barremian boundary falls in the interval between this sample and a sample from near the base of the sandstones (433·8 m) which gave a Hauterivian date (Hughes and MacDougall 1990.

In this paper we specifically restrict 'Topley's Bed 5' to the glauconitic sandstones between 431·8 m and 433·9 m. Moreover, it is evident that this bed underlies Topley's Bed 4 as defined above (Bed 6 in the original borehole classification) and should more properly be numbered 'Bed 3'; albeit



TEXT-FIG. 3. Charophyte succession in the Purbeck and Wealden beds of southern England and correlation with the ostracod Assemblages of Anderson (1985). Dashed lines refer to related unspecified forms.

there is a thin sand at the top of unit c. The transition from brackish-marine to freshwater conditions above this bed clearly marks a significant event at or about the Hauterivian–Barremian boundary (Allen 1989; Allen and Wimbledon 1991). This amendment to the classification of the Warlingham sequence invites reassessment of the correlation with other occurrences of Bed 3 (and subordinate units) which show brackish influences at outcrop in the Weald (Worssam and Ivimey-Cook 1971, p. 29; Worssam 1978, p. 8).

Charophyte succession (Hastings Beds and equivalent strata)

Above the Cinder Bed Member, there are large gaps in the charophyte succession. The Ashdown Beds, as well as the Lower and Upper Tunbridge Wells Sands, have yielded only insignificant charophyte material.

Undefined Zone 5 = Interregnum 4–6. This corresponds to the interval between the last occurrence of *Clavator reidi* and the first occurrence of *Flabellochara xiangyunensis* in the Wadhurst Clay of the Weald. This Zone has not yet been recognized in Dorset. The interval represented by Zone 5 corresponds to the highest part of the Durlston Formation and to the Ashdown Beds, which are interpreted as fluvial deposits (Allen 1989), not favourable to the preservation of charophytes. Taxa identified from this zone comprise *Tolypella* sp., *Peckisphaera knowltoni* (Seward) Schudack, and incompletely calcified utricles of *Flabellochara* (see Appendix 1 for sample location). The Ashdown Beds are currently dated as Berriasian–early Valanginian on palynological evidence (Allen and Wimbledon 1991).

Zone 6. This is defined as the interval between the first occurrence of *Flabellochara xiangyunensis* in the Wadhurst Clay of the Weald and that of *Clypeator britanicus*. The lowest occurrence of *F. xiangyunensis* is at 59·00–59·50 m depth in the Glynleigh Borehole. An important additional species is *Sphaerochara* aff. *andersoni*.

Zone 6 has been identified in Wadhurst Park No. 3 Borehole at an horizon in the upper part of the Wadhurst Clay corresponding to the Hawkhurst ostracod faunicycle. On the basis of the occurrence of *Flabellochara xiangyunensis*, Zone 6 can be broadly correlated with the Valanginian *F. xiangyunensis–Clypeator zongjiangensis* Zone established by Wang and Lu (1982) in China. With regard to the European biozonation, Zone 6 seems to correspond to the *Embergerella stellata* Zone, defined by the first occurrence of this species in the Lower Valanginian of Maestrazgo (north-east Spain), dated by orbitoline foraminifers (Martin-Closas and Salas 1988). This dating is compatible with the age attributed to the Wadhurst Clay by Allen and Wimbledon (1991).

Zone 7. This is defined as the interval corresponding to the range of *Clypeator britannicus*, recorded in the Kingsclere Borehole from 305·7–306·6 m; this is above beds between 311·8–354·8 m with ostracod assemblages which indicate a correlation with the whole of the Wadhurst Clay (Anderson and Shephard-Horn 1967). Because this taxon has not been recognized elsewhere, only the evolutionary stage reached enables its occurrence to be dated tentatively. Apparently transitional between the Berriasian, *Clypeator discordis* and the upper Hauterivian–Barremian, *C. combei*, *C. britannicus* can be inferred to be of Valanginian–early Hauterivian age. A probable Valanginian age is, however, only compatible with its occurrences in the Kingsclere Borehole, taking the tentative classification of the beds in question as equivalent to the Grinstead Clay (cf. Lees and Taitt 1945; Anderson 1985).

Undefined Zone 8 = Interregnum 7–9. This corresponds to the interval between the last occurrence of *C. britanicus* and the first occurrence of *Triclypella calcitrapa* in the middle part of the Weald Clay in the Weald (Warlingham Borehole). This interval is provisionally inferred to equate with the Upper Tunbridge Wells Sand and much of the lower part of the Weald Clay, which have not yielded charophytes.

Following the current dating of the various lithological subdivisions of the Wealden Beds (Allen and Wimbledon 1991), this interval may include the upper part of the Valanginian *Embergerella stellata* Zone and the Upper Hauterivian *Globator trochiliscoides* (primitive form) Zone defined in the Tethyan areas (Martin-Closas and Salas 1989).

Charophyte succession (*Weald Clay and equivalent strata*)

Charophytes of zonal significance occur above Bed 2 and its correlatives in the Weald Clay of the Weald and also at the base of the Vectis Formation, in the Isle of Wight, the latter representing the highest occurrence of charophytes in the Mesozoic of southern England.

Zone 9. This is defined as the interval between the first occurrence of *Triclypella calcitrapa* and the first and only occurrence of *Ascidiella iberica* in the Weald (Warlingham Borehole, 430·0 m). The zone is present in beds immediately below and above the top of the Small-'*Paludina*' Beds, including Bed 3. Important species are *Clypeator combei* and *Sphaerochara andersoni*.

Zone 9 has been identified in the Warlingham, Ripe and Hailsham boreholes, near the base of the upper part of the Weald Clay. Palynofloras from the Ripe Borehole (Feist and Batten 1990) and from the Warlingham Borehole (Hughes and McDougall 1989) indicate that this zone may straddle the Hauterivian–Barremian boundary.

Zone 10. This is defined as the interval between the first and only occurrence of *Ascidiella iberica* and that of *Atopochara triquetra* (advanced) in southern England. The zone is present, in the lower part of the upper division of the Weald Clay, in beds above the equivalent of Bed 3 in the Warlingham Borehole, where *A. iberica* occurs at 430·0 m. The base of Zone 10 can be dated imprecisely (as late Hauterivian/early Barremian) from records of the index species in Spanish localities. The occurrence of *A. iberica* in the Warlingham Borehole indicates an early Barremian age. Important species are *Atopochara triquetra* (primitive), *Clypeator combei*, *Triclypella calcitrapa* and *Sphaerochara andersoni*.

Zone 10 corresponds to the El Mangraner charophyte Zone of Grambast (1974), defined in north-east Spain and also identifiable in the Pre-Dobrogean Depression, Ukraine (Shaikin 1976). The El Mangraner Zone ranges from the Lower Barremian to possibly the Upper Hauterivian from foraminifer evidence (Martin-Closas and Peybernes 1987; Martin-Closas and Salas 1989).

Zone 11. This is defined as the interval based on the range of *Atopochara triquetra* (advanced). The zone is represented in the Cowleaze Chine Member at the base of the Vectis Formation, in the Isle of Wight. Important additional species are *Clypeator combei*, *Triclypella calcitrapa* and *Peckisphaera verticillata*.

Zone 11 corresponds to the late Barremian San Carlos charophyte Zone of Grambast (1974) and is identifiable in the La Ruchère section in the Jura (Mojon 1988) dated by foraminifers (Schroeder *in* Mojon 1988) as Early Aptian.

The occurrence of advanced forms of *A. triquetra* is considered as more significant than that of the persistent accompanying species *C. combei*, previous records of which limited its range to the lower Barremian (Grambast 1970; Martin-Closas and Salas 1989). This interpretation fits with palynofloras characterizing the upper Barremian (Feist and Batten 1990).

THE PURBECK GROUP AND THE PROBLEM OF THE JURASSIC–CRETACEOUS BOUNDARY

The most complete charophyte succession in the Purbeck Group has been found in the boreholes from the Weald. In Dorset, only the sequences from the upper Soft Cockle to the Intermarine members have yielded charophytes so far, well above the level where the base of the Berriasian has been placed (Allen and Wimbledon 1991).

Weald

The Purbeck strata of the Weald rest on marine Portlandian, but the age, based on ammonite data, of the highest marine sediments below the contact varies throughout the basin. In the Fairlight Borehole and in the gypsum mines in the southern Weald, the Gypsiferous Beds rest, locally with erosional contact (Brightling Mine), on sandstones of the *Glaucolithites glaucolithus* Zone, i.e. equivalent to the middle part of the Portland Sand Formation of Dorset. By contrast, in the Warlingham Borehole (northern Weald), the Gypsiferous Beds rest on the lower part of the Portland Stone Formation, *Galbanites* (*Kerberites*) *kerberus* Zone; it has been suggested (Wimbledon 1980) that there was no hiatus between the highest marine Portlandian and the onset of Purbeck facies sedimentation, implying that the lower part of the Purbeck Beds in this area correlated with the *Titanites anguiformis* Zone Portland Freestone of Dorset. Although these data could be taken to demonstrate that the onset of Purbeck facies was diachronous within the Wealden basin, Worssam and Ivimey-Cook (1984) argued that this apparent diachroneity might have resulted from a non-sequence in the southern part of the area caused by intra-Portlandian movement of the Portsdown–Paris Plage Swell and that the beginning of Purbeck-type sedimentation (as distinct from the date of the highest underlying marine Portlandian) might be essentially synchronous throughout the basin.

The Broadoak Calcareous Member of the Lulworth Formation can be subdivided biostratigraphically by means of three successive species of the *Globator* lineage. The inferred Tithonian local charophyte Zone 1 is recognized by the presence of *G. rectispirale* in the basal part of the Member in the Fairlight Borehole, while the Lower Berriasian local charophyte Zone 2, characterized by *G. praecursor*, is represented in four boreholes: Fairlight, Warlingham, Broadoak and Brightling (see Appendix 1). The boundary between zones 1 and 2 appears to occur at about the level of the Mountfield Adit Limestone (Lake and Holliday 1978, fig. 3), i.e. near the base of the Broadoak Calcareous Member and a short distance above the Gypsiferous Beds Member. *G. protoincrassatus*, which succeeds *G. praecursor* in the lower part of the Lower Berriasian, has also been found in the Weald, but only in the Fairlight Borehole.

The fact that charophyte Zone 1 was recognized only in the Fairlight Borehole does not seem sufficient evidence to demonstrate that Purbeck sedimentation began earlier in the southern Weald; the beds spanned by local charophyte Zone 2 in the Warlingham Borehole, in the northern Weald, are situated 30 m above the marine Portland Beds and this interval has yielded ostracods belonging to Assemblage 1 of Anderson (1985) as in the basal Purbeck beds of the Fairlight Borehole, corresponding to local charophyte Zone 1.

Dorset

The dating, in terms of both Tethyan and Boreal ammonite biostratigraphy, of the onset of non-marine (Purbeck facies) sedimentation and of the various members comprising the Purbeck Group remains unresolved. Recent interpretations of the possible correlations between the marine and non-marine successions are based on global sea-level changes (Hoedemaeker 1991, fig. 1), but some additional evidence is provided by palynomorphs and magnetostratigraphy.

Hunt (1985) drew the base of the *Apiculatisporis verbitskayae* miospore Biozone near the top of a group of thin limestones at an horizon only 3 m above the base of the Cypris Freestones Member. In a subsequent paper (Hunt 1987, fig. 11.2), he took this floral change to mark the base of the Berriasian. It is possible that these limestones approximate to the level of the Mountfield Adit Limestone of the Weald, which marks the boundary between local charophyte zones 1 and 2 and the inferred position of the Tithonian–Berriasian boundary (see above). It is noteworthy that a significant change in the miospore assemblage in Purbeck appears to coincide with a change in the charophytes in the Weald. However, the Cypris Freestones palynomorphs and the overlying ostracods are stated to permit correlation with the *Pseudosubplanites grandis* ammonite Subzone of the Berriasian stratotype (Allen and Wimbledon 1991; Wimbledon, pers. comm. 1994), implying that the base of the Berriasian as understood here (i.e. the base of the underlying *Berriasella jacobi* ammonite Subzone) lies below the Cypris Freestones and possibly approximates to the base of the Purbeck Limestone Group. This latter interpretation is supported by preliminary magnetostratigraphical studies of the Purbeck stratotype (Ogg *et al.* 1991), but does not agree with the correlations of Hoedemaeker (1991, fig. 1), who equated the greater part of the basal Purbeck succession below the Cypris Freestones with the terminal Tithonian '*Durangites*' ammonite Zone.

In Dorset, samples collected from the lower part of the Lulworth Formation were barren of charophytes and there is therefore no direct evidence for the recognition of the Jurassic–Cretaceous boundary. The type material of the supposed new taxon *Clavator westi* Costin (*in* Barker *et al.* 1975) from the Charophyte Chert, near the base of the Lulworth Formation at Portesham Quarry, is indeterminate (see discussion in Appendix 2). The lowest occurrence of determinable charophytes is in the upper part of the Soft Cockle Member at Durlston Bay; Bed DB70 (Clements, *in* Cope *et al.* 1969; Clements 1993) has yielded *Globator protoincrassatus*, which is the index of local charophyte Zone 3 and of Mojon's Zone M2 in the Jura, and is lower (but not basal) Berriasian and equivalent to the *Pseudosubplanites grandis* Subzone of the *grandis* ammonite Zone. This dating is supported by early Berriasian miospores and dinoflagellates in a sample from the top of Bed 43 in the lower part of the Soft Cockle Member (Batten *et al. in* Lord and Bown 1987).

Charophyte Zone 4 covers the interval from the Cherty Freshwater Member to the Intermarine Member. The charophyte assemblage, with *Flabellochara grovesi*, is that studied by Harris (1939).

By comparison with the Jura and north-western Germany, the Dorset succession from the Soft Cockle to the Intermarine members is attributable to the Lower, not basal, Berriasian.

Wiltshire

The dating of the 'Swindon Series' has always been a matter of controversy (Sylvester-Bradley 1941, 1942; Arkell 1942). Wimbledon (1980, fig. 15) showed the Town Gardens Member divided between the *kerberus* and *anguiformis* zones (by implication assigning the Swindon Roach to the latter zone), with the overlying Purbeck Limestone Formation also placed in the *anguiformis* Zone, but there is no hard evidence for this interpretation (Wimbledon, pers. comm. 1992). The marine Swindon Roach, despite its general lithological and faunal similarity to the *anguiformis* Zone Roach of the Isle of Portland (particularly in the occurrence of the 'Portland screw' *Aptyxiella portlandica*) has so far yielded no ammonites.

Arkell (1942) considered that the 'Swindon Series' equated with the 'Middle Purbeck' by reference to the charophytes, which he noted were particularly characteristic of and common in the 'Middle Purbeck' of Dorset, but which he mistakenly stated were not found below in the 'Lower Purbeck'. However, Sylvester-Bradley (1942) and all subsequent workers (see above) have emphasized that the ostracods point unequivocally to a correlation between the 'Swindon Series' and the basal Purbeck of Dorset, whilst not excluding the possibility of the Swindon succession being a Purbeck-facies equivalent of the highest Portland Beds. The entire succession, which contains *Cypridea dunkeri papulata* throughout, belongs to the lowest Lower Purbeck ostracod assemblage (Assemblage 1), comprising the Quainton, Warren, Ridgeway and Stair faunicycles in ascending order (Anderson 1985, fig. 5), of which the first three were recognized at Swindon by Anderson. The absence of any members of the *Cypridea granulosa granulosa–C. granulosa fasciculata* lineage in the higher part of the 'Swindon Series' rules out any correlation of these beds, particularly the Chara Marls, with the charophyte-rich higher part of the Lulworth Formation.

The general consensus is to correlate the entire 'Swindon Series' with the uppermost member (Portland Freestone) of the Portland Stone Formation of the Dorset coast, together with the basal beds of the Dorset Purbeck sequence (Caps, Dirt Beds and Broken Beds). This means that the charophyte assemblages at Swindon are *older* than any other charophytes discussed here from the British Purbeck, with the possible exception of the largely indeterminate material described from the Charophyte Chert of Portesham Quarry (Barker *et al.* 1975; and this paper).

The Town Gardens Quarry at Swindon provides the northernmost exposure of Purbeck strata in Britain that yields charophytes. A preliminary study of the charophyte floras (Harris *in* Sylvester-Bradley 1941) identified *Flabellochara grovesi* and *Clavator reidi*, indicating a broad correlation with the 'Middle Purbeck Beds' of Dorset. Re-evaluation of the charophytes has now shown that the entire succession is characterized by *Clypeator discordis* and the primitive form *Clavator* aff. *reidi*, all specimens formerly attributed to *Flabellochara grovesi* having been misidentified. By extrapolation from the Brouco section, Portugal, where *Clavator discordis* co-occurs with *Globator rectispirale*, and on the basis of the occurrence of *Clavator* aff. *reidi*, the Swindon succession, including the Chara Marls near the top, is tentatively assigned to the Tithonian local charophyte Zone 1, albeit in the absence of the zonal index. This new interpretation is supported by the ostracod evidence, which places the Swindon succession in ostracod Assemblage 1, i.e. equivalent to the basal stratotype Purbeck succession below the Cypris Freestones. It also agrees with the correlation scheme presented by Hoedemaeker (1991, fig. 1), in which the three ostracod faunicycles (Quainton, Warren and Ridgeway) recognized by Anderson (1985) at Swindon are equated with the terminal Tithonian '*Durangites*' ammonite Zone. There is no evidence at Swindon for the Lower Berriasian local charophyte Zone 2.

CONCLUSIONS

For the first time, a stratigraphical study based on charophytes has been undertaken of the whole of the Purbeck and Wealden sequence of southern England. In contrast with previous views, this group provides a useful tool for subdividing and correlating the non-marine sequences between the Portland Stone and the base of the Lower Greensand. We have subdivided the succession into eleven local charophyte zones, of which two (zones 5 and 8) must remain uncharacterized intervals at present. This new zonal scheme provides useful correlations between successions in the Weald, Dorset and Wiltshire. Because of the wide distribution of most species at this time, direct correlations can be established between the Boreal and Tethyan realms. The Upper Tithonian local charophyte Zone 1 and the Lower Berriasian local charophyte zones 2, 3 and 4 established here can also be recognized in the Tethyan Realm.

Two key indirect correlations can be made between the charophyte local zonal scheme for the Purbeck Limestone Group and marine successions in the Tethyan and Boreal Realms. The zonal index of the *Globator rectispirale* local charophyte Zone 1 can be recognized in Algeria below beds with an A2/A3 calpionellid assemblage, correlated with the Upper Tithonian '*Durangites*' ammonite Zone of the Tethyan Realm. The *Flabellochara grovesi* local charophyte Zone 4 embraces the Cinder Beds Member at the base of the Durlston Formation. This bed is taken to correlate with the *Praetollia runctoni* ammonite Zone at the base of the Ryazanian Stage of the Boreal Realm and has been equated approximately with the base of the *Strambergella occitanica* ammonite Zone of the Tethyan Realm.

The Jurassic–Cretaceous boundary can be inferred on charophyte occurrences (the boundary between local charophyte zones 1 and 2) to be located near the base of the Broadoak Calcareous Member of the Lulworth Formation of the Purbeck Limestone Group of the Weald. The boundary is situated at about the level of the Mountfield Adit Limestone, which may approximate to the basal group of limestones of the Cypris Freestones Member of the stratotype Purbeck Group succession in Dorset and the base of the *Apiculatisporis verbitskayae* miospore Zone. The Jurassic–Cretaceous boundary is understood here as the base of the Berriasian Stage of the Tethyan Realm, i.e. (following Anon. 1975) the base of the *Berriasella jacobi* Subzone of the *Pseudosubplanites grandis* ammonite Zone.

If the base of the Berriasian approximates to the base of the Cypris Freestones, the new charophyte data accord with Hoedemaeker's (1991, fig. 1) correlation diagram. Thus, the gypsiferous basal beds could represent the Tithonian '*Durangites*' Zone (Tidalites de Vouglans of the Jura) and the base of the Cypris freestones could equate with the base of the (Berriasian) Goldberg Formation, within which the *Globator* lineage was first recognized.

The charophyte biostratigraphy supports the previous ostracod-based correlations between the Purbeck and Wealden successions of Dorset and the Weald respectively. A reassessment of the charophyte and ostracod data from the Town Gardens Quarry, Swindon, allows this succession to be attributed tentatively to the Upper Tithonian local charophyte Zone 1 and equated indirectly with the '*Durangites*' ammonite Zone of the Tethyan Realm. This succession is divided between the *Galbanites kerberus* and *Titanites anguiformis* ammonite zones (Wimbledon 1980); the charophytes thus provide indirect evidence of the contemporaneity of these boreal ammonite zones with the Tethyan '*Durangites*' Zone.

For the Wealden Supergroup, the charophyte data, supported by preliminary palynological indications from Professor D. J. Batten, allow us to locate the Hauterivian–Barremian boundary near the base of the upper division of the Weald Clay in the Weald. The Upper Barremian is identified in an equivalent of the topmost Weald Clay, at the base of the Vectis Formation of the Isle of Wight.

In addition to these stratigraphical results, the work has provided new data on charophyte evolution. The oldest and most primitive representative of the *Globator* lineage has been found in the Fairlight Borehole. On the other hand, correlations establish the presence of the genus *Clypeator* in the Upper Jurassic; this supports the views of Martin-Closas and Serra-Kiel (1991), who considered the Upper Jurassic to be a period of charophyte diversification. The appearance of *Clypeator* before *Flabellochara* suggests that the two genera have a separate origin.

The study of Jurassic–Cretaceous charophytes from southern England is far from complete and the local zonal scheme presented here must be regarded as provisional. Further collecting from the incompletely sampled Purbeck Limestone Group of Dorset should lead to refinements of the zonal scheme for this part of the succession. Future investigations could examine the extent to which changes in taxonomic diversity and degree of calcification are controlled by palaeoenvironmental changes.

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APPENDIX 1 – DISTRIBUTION OF CHAROPHYTES IN BOREHOLES IN THE PURBECK AND WEALDEN OF SOUTHERN ENGLAND

The distribution of charophyte species found in borehole material is described in descending order. Sample numbers with the prefix Mik(M), MPA and SAM refer to the British Geological Survey collections at Keyworth, NHM numbers to the National History Museum, London, SWF to the Senckenberg Museum, Frankfurt, and CF to the Laboratoire de Paléobotanique, Université de Montpellier.

Warlingham Borehole, Surrey (Worssam and Ivimey-Cook 1971)
This includes the most complete succession of charophyte floras and is taken as a reference section, supplemented by data from the Purbeck Group in the Fairlight Borehole.

Weald Clay, lower portion of the upper part
430·0 m. Samples Mik(M) 1068 and SAM 884: *Ascidiella iberica*, *Atopochara triquetra* (primitive), *Triclypella calcitrapa*, *Sphaerochara andersoni*.
430·4 m. Sample Mik(M) 2493: *Clypeator combei*, *T. calcitrapa*, *S. andersoni*, stems.
430·7 m. Sample Mik(M) 1074 and SAM 886: *T. calcitrapa*, *S. andersoni*.
Ashdown Beds
573·6 m. Sample Mik(M) 1545: Small-sized gyrogonites of Characeae, *Tolypella*?
581·7 m. Sample Mik(M) 1558: Characeae genus et species indet.
Purbeck Group (all samples from the Lulworth Formation)
612·1 m. Sample Mik(M) 1758 and SAM 1346 (ex Bp 4971): *Porochara maxima*, Clavatoraceae gen. et sp. indet., stems.
612·3–612·4 m. Sample Mik(M) 1759: *Clavator reidi* (one utricle, with slightly spiralized cells), *Porochara maxima*, stems.

614·2–614·4 m. Sample Mik(M) 1760: *Latochara* sp., *C. reidi* (utricles with well spiralized cells), *Aclistochara* sp., stems.
614·8 m. Sample Mik(M) 1775 and SAM 1360 (ex Bp 5012): *C. reidi* (utricles with spiralized cells).
625·3 m. Sample Mik(M) 1856 and SAM 1403: *Globator praecursor*, *Clavator* aff. *reidi*.
631·9 m. Sample SAM 1424: *C.* aff. *reidi*.

Ripe Borehole, Sussex (Lake and Young 1978)
Weald Clay
154·00–154·50 m. Sample Mik(M) 3927 and MPA 25418: *Triclypella calcitrapa*, *Sphaerochara andersoni*, *Clypeator combei*.
159·50–160·00 m. Sample Mik(M) 3935 and MPA 25419: *Clypeator combei*.

Hailsham Borehole, Sussex (Lake and Young 1978)
Weald Clay
16·50–17·00 m. Sample Mik(M) 3736: *T. calcitrapa*, *S. andersoni*.
29·50–30·00 m. Sample Mik(M) 3780: *C. combei*.
38·00–38·50 m. Sample Mik(M) 3790: *T. calcitrapa*.

Wadhurst Park No. 3 Borehole, Sussex (Anderson and Shephard-Thorn 1967)
Wadhurst Clay
6·7–7·0 m. Sample Mik(M) 1987 and SAM 3779: *Flabellochara xiangyunensis*, *Sphaerochara* aff. *andersoni*.
7·3–7·6 m. Sample Mik(M) 1993 and SAM 3781: *Flabellochara xiangyunensis*.
16·8–17·0 m. Sample Mik(M) 2026: *Flabellochara* sp. indet.

Glynleigh Borehole, Sussex (Lake and Young 1978)
Wadhurst Clay
59·00–59·50 m. Sample Mik(M) 3697: *Flabellochara xiangyunensis*, *Sphaerochara* aff. *andersoni*.

Kingsclere Borehole, Hampshire (Lees and Taitt 1945)
?Grinstead Clay (equivalent)
305·7 m. Sample Mik(M) 2489, ex. Mik(M) 301: *Clypeator britannicus*.
306·6 m. Sample Mik(M) 2490, ex. Mik(M) 327–9: *Clypeator britannicus*, *Sphaeorchara* aff. *andersoni*.

Robertsbridge Bypass No. 15 Borehole, Sussex (OS TQ 7391 2523)
Wadhurst Clay
2·9–3·0 m. Sample 15/6, University of Brighton, CF 2773b. Stiff olive-grey, slightly shaly clay: *Flabellochara* sp. (incompletely calcified utricles), *Sphaerochara* aff. *andersoni*.
12·2–12·3 m. Sample 15/18, University of Brighton, CF 2773a. Dark greenish shaly clay with fossil shell fragments: *Sphaerochara* aff. *andersoni*.

Kitchenham Dam Borehole No. K4, Sussex (OS TQ 6816 1313)
Wadhurst Clay
28·30 m. Sample per University of Brighton, CF 2774/1. Light greenish grey, partly friable clay: *Flabellochara xiangyunensis*.

Fairlight Borehole, Sussex (Holliday and Shephard-Thorn 1974)
Purbeck Group (Plant and Bone Beds Member)
263·3–263·7 m. Sample Mik(M) 4159: ?*Tolypella*.

Purbeck Group (Broadoak Calcareous Member)
273·4–273·7 m. Sample Mik(M) 4192: *Flabellochara* cf. *grovesi*.
273·7–274·0 m. Sample MPA 25422: *Clavator reidi* (with vertical cells), *Flabellochara grovesi*.
280·1–280·4 m: *Flabellochara grovesi*, *Clavator reidi* (spiralized).
281·0–281·3 m: *F. grovesi*, *C. reidi*, small-sized Characeae, oospores.
293·2–293·5 m. Sample MPA 25425: *Globator protoincrassatus*.
296·0–296·3 m. Sample MPA 25426: *G. praecursor*, *Clavator* aff. *reidi*.
317·6–317·9 m: *Globator rectispirale*, nodosoclavatoroid utricles.

Broadoak Borehole, Sussex (Lake and Holliday 1978)
Purbeck Group (Broadoak Calcareous Member)
71·50–72·00 m. Sample Mik(M) 4333: *Clavator reidi* (vertical cells).
111·50–112·00 m. Sample Mik(M) 4296: *Globator praecursor.*

Brightling No. 27 Borehole, Sussex (Anderson and Bazley 1971)
Purbeck Group (Broadoak Calcareous Member)
270·6 m. Sample Mik(M) 2651: *G. praecursor.*

APPENDIX 2 – DISTRIBUTION OF CHAROPHYTES IN PURBECK AND WEALDEN OUTCROPS IN SOUTHERN ENGLAND

For the Purbeck Limestone Group, specimens were collected by MF in the classic sections along the Dorset coast and at two localities in the Swindon Marshes: Town Garden Quarry, Swindon and the Upwey section. Sediments collected in the basal Purbeck beds of the Isle of Portland did not yield any charophytes. MF has also revised the specimens from the same areas that are housed in the Natural History Museum (specimen numbers prefixed BMNH-V), notably the important material studied by Harris (1939). Wealden charophyte floras have been collected from a quarry near Capel, Surrey, and on the south-west coast of the Isle of Wight (specimens CF, charophyte collections, University of Montpellier). The distribution of charophyte floras found at outcrop is given below.

Wealden Supergroup
Cowleaze Chine. South-west coast of the Isle of Wight (OS SZ 444 801). There are three levels with charophytes, at the base of the Vectis Formation (Stewart 1981).
CF 2777b. 170 m west of Cowleaze Chine; dark grey marls: *Atopochara triquetra* (advanced), *Clypeator combei, Peckisphaera verticillata.*
CF 2777a. 150 m west of Cowleaze Chine; dark grey marls below a bed of light grey sands 0·3 m thick: charophyte flora as above.
CF 2776. 0·1 m above the sand bed; dark grey marls, with white mollusc shells and fish teeth: *C. combei.*

Butterley Brickworks Pit (*formerly Clock House Pit*). Capel, Surrey (Worssam 1978) (OS TQ 175 384).
CF 2771. Weald Clay, below Bed 3, bed 33 in Worssam (1978, p. 16). Charophytes were collected in 1986 from a shaly clay below a sandstone with *Ophiomorpha: Sphaerochara* sp.

Stream section, 500 m east of Freechase. Near Warninglid, Sussex (OS TQ 2442 2518).
E276, British Geological Survey, Keyworth. Wadhurst Clay, sample of purple shales from beds high in the formation: *Flabellochara xiangyunensis.*

Fairlight section. Sussex.
Hastings Beds, 'Fairlight Clay', Sample BMNH-V1070: *Peckisphaera knowltoni* (Seward) Schudack; internal mould of a ?Characeae.

Purbeck Limestone Group of Dorset
Durdle Door.
CF 2781a–b. Lulworth Formation: Broken Beds and Caps: ostracods. No charophyte seen.
Harris (1939): Below chert: *Perimneste horrida.*
CF 2781. Just below the Cinder Bed [Member], in the Lulworth Formation. Marl with gypsum.
CF 2781c: *Flabellochara grovesi, Clavator reidi.*
CF 2781d: *Flabellochara grovesi.*

Durlston Bay, Swanage. (OS SZ 040 786).
Neale and Mojon sample. Higher part of Soft Cockle Member, Lulworth Formation: Bed DB 70 of Clements (*in* Cope *et al.* 1969; Clements 1993): *Globator protoincrassatus.*

Worbarrow Tout. See Ensom (1985).
CF 2783. Above the Cinder Bed [Member], in the Durlston Formation: *Porochara* sp., *Clavator reidi.*

Mupe Bay. See Arkell (1947*a*).

Harris (1939) reported *Perimneste horrida* from this locality, probably from the Charophyte Chert, Cherty Freshwater Member, Lulworth Formation.

CF 2785. 0·8 m above the chert, and below the Cinder Bed [Member]: *Flabellochara grovesi.*

Durlston Bay. Swanage (Clements *in* Cope *et al*. 1969; Clements 1993; El Shahat and West 1983).

CF 2779a–b. Mammal Bed, in the Marly Freshwater Member, Lulworth Formation: *Porochara* sp., *Clavator reidi.*

CF 2780b. Above the Cinder Bed, in the Durlston Formation: *Porochora* sp., *Clavator reidi.*

Portesham Quarry. Near Abbotsbury (OS SY 611 859).

Harris (1939) reported *Perimneste horrida, Clavator reidi* and *C.* (i.e. *Flabellochara*) *grovesi* (holotype) in 'Portesham or near Portesham', from Reid and Groves collection. Portesham Quarry is the type locality of *Clavator westi* (Barker *et al*., 1975). The type material of this supposed new taxon comprises nodosoclavatoroid utricles and vegetative fragments which could correspond to any Clavatoroideae: '*C. westi*' cannot therefore be considered as a species in the traditional sense of charophyte taxonomy (Feist and Grambast-Fessard 1991).

Sample BMNH-V26280, Reid and Groves Collection: *Clavator reidi.*

Poxwell Road cutting. Dorset.

Bed 33 of Sylvester-Bradley (1949). BMNH-V26181: *Flabellochara grovesi.*

Purbeck Limestone Group of Swindon Marshes

Town Gardens Quarry. Swindon, Wiltshire. Section after Sylvester-Bradley (1941).

CF 2789a. 'Lower Purbeck Beds'. Exposure II. Lower Pebbly Beds (base): *Clypeator discordis*. Ostracoda: *Cypridea dunkeri papulata*. Foraminifera: *Lenticulina muensteri.*

CF 2789b. 0·3 m above: *Clavator* aff. *reidi.*

CF 2790. Cythere Marl: *Clypeator discordis.*

'Middle to Upper Purbeck Beds'. Exposure IV. Middle Pebbly Bed. Sample TCQ-IV, collected by Dr H. Malz, Senckenberg Museum, Frankfurt a. Main and sample CF 2792: *Latochara* aff. *bitruncata*, nodosoclavatoroid utricles, *Clypeator discordis.*

Exposure III. Chara Marls. Sample TGQ-III of H. Malz and sample CF 2791a, at the base of the marls: *Clypeator discordis, Clavator* aff. *reidi* (with vertical and slightly spiralized cells).

Sample CF 2791b–c (laterally, at the top of the marls): *Clypeator discordis, Clavator* aff. *reidi*, nodosoclavatoroid utricles.

Purbeck Limestone Group of the Vale of Wardour, Wiltshire (see Harris 1939).

Chicksgrove quarry, near Tisbury. Sample CF 2788, grey shaly marls, 1 m above the Portland Stone: *Latochara* aff. *bitruncata*, Clavatoraceae gen. et sp. indet.